A STUDY OF THE CAUSES, CONTROL, AND MEASUREMENT OF MAN-MADE RADIO FREQUENCY INTERFERENCE GENERATED BY NON-COMMUNICATION EQUIPMENT

DONALD D. ALLGAIER
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by

Donald D. Allgaier

Lieutenant, United States Navy

and

James E. Galloway

Lieutenant Commander, United States Navy

Submitted in partial fulfillment of
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ABSTRACT

In order to make maximum use of the radio frequency spectrum the effects of radio frequency interference must be minimized. A portion of this interference is generated by man-made non-communication type equipment such as ignition systems, electric motors and generators, arc welders, power lines, etc. A review of the literature revealed an extensive amount of work reported, primarily, in the form of technical articles and reports. In order to provide a single reference source, the authors have reviewed all available material on man-made radio frequency interference published during the past 30 years. Approximately 1000 references, many with abstracts, have been categorized in the general areas of causes, control, and measurement techniques. Recommendations for areas of further investigation are also included.

The writers wish to express their appreciation for the assistance and encouragement given them by Professor P. E. Cooper and Associate Professor W. E. Norris of the U. S. Naval Postgraduate School in this study. In addition, the writers wish to express their appreciation to the staff of the Technical Library, U. S. Naval Postgraduate School whose continuing assistance made this detailed study possible.

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CHAPTER I

INTRODUCTION

Man is becoming more and more aware that he is living in an "age of noise". In the case of radio communication links noise takes the form of radio frequency interference. Much of this interference is generated by the communication equipments themselves, for example, in the form of spurious emissions from transmitters and radiation from receiver local oscillators. A great deal of investigation and study is being conducted to make the electromagnetic environment as compatible as possible for the ever increasing numbers of communication equipments. The spectrum signature program of the Department of Defense is representative of the effort in this area.

Another major source of radio interference is that generated by non-communication type equipment such as ignition systems, electric motors and generators, power lines, arc welders, diathermy machines, etc Garlan and Davis, of the Federal Communications Commission, in a paper on man-made noise commented as follows:

> It is quite generally recognized that radio frequency generating devices are used in industry for many purposes quite different than that of providing communication. What is not so generally appreciated is the number of such equipments in use, the amount of radio frequency energy that is generated and the limitation that these devices impose on communication circuits. The largest radio frequency power generating equipments of the non-communication type are the industrial heaters. A survey in April 1956 showed that more

> than 30,000 industrial radio frequency heating equipments had been sold up to that date having a combined generating capacity of more than 160 million watts.

Our choice of man-made radio frequency interference from non-communication equipment as an area of study stemmed largely from its close association with our future duties as U. S. Naval Civil Engineer Corps Officers. In the area of electronics these duties will include the following:

(1) Site selection and layout for shore electronic facilities;

(2) Administration of contracts involving the construction of shore electronic facilities;

(3) Maintenance of shore electronic facilities as a Public Works Officer;

(4) Assignment as staff electronic specialist at the Naval District or Bureau level.

It is intended that the material presented in this thesis will provide needed guide lines and reference material covering radio interference problems that are likely to arise in the course of the above listed duties. Interference generated by natural causes, i.e. atmospheric and galactic sources, have not been included. Reference to man-made interference generated by communication equipment has also been omitted as it was not deemed to fall within the scope of the duties outlined.

In achievement of the above objective the material has been treated in a semi-bibliographical style. It has been

organized in the following manner:

(1) Causes -- ignition, industrial equipment, power lines, etc.;

(2) Control -- suppression and shielding;

(3) Measurement -- equipment and methods.

Within each chapter the specific topic is discussed in general terms, followed by a bibliography arranged alphabetically by title. All available abstracts and source reference material from both civilian and government sources (including foreign if in English or with an English translation) have been included.

Conclusions and recommendations for future areas of investigations are included in Chapter XIV.

CHAPTER II

RADIO FREQUENCY INTERFERENCE

To establish a common basis of understanding, a definition and description of some of the characteristics of radio frequency interference (RFI) are in order. For this thesis, radio frequency interference shall be defined as any electrical disturbance which causes an undesirable response or malfunction in any electronic circuit.

RFI can be classified according to its spectral distribution as either broadband or narrowband interference. Under the broadband classification, there is impulse interference and random interference. Impulse interference is characterized by a systematic or periodic repetition of pulses. Random interference is described as pulses having no clear or definite repetition rate. The term "broadband" indicates that the interference is not confined to one specific frequency but may be spread over a large range of frequencies. It may be shown mathematically that a pulse is equivalent to a large group of frequencies having various amplitudes. In ref. (66), a qualitative summary of such a mathematical treatment is given. It is pointed out that (1) the spread in frequency is roughly inversely proportional to the duration of a pulse, (2) the more rapidly a pulse amplitude builds up or falls off, the greater is that portion of its energy which is contained in the high-frequency components, and (3) the longer the duration of a

pulse, the greater is that portion of its energy which is contained in low-frequency components. Narrowband interference is characterized by the fact that it is limited to a discrete frequency.

RFI can also be classified according to its mode of transmission. The general modes are conduction, radiation, and circuit coupling. RFI can be conducted whenever there is a path for current to flow in a complete loop. Sometimes the return path may be through a mutual capacitance or through ground. Radiation, in the strict sense of the term, is used to describe the phenomena of electromagnetic waves spreading out in space from a source according to the laws of propagation. This is one of the modes of transmission of RFI, but often circuit coupling is included in "radiation". Circuit coupling includes both mutual inductive and mutual capacitive coupling. Confusion between a radiated, or "far-field", and a coupling, or "near-field", mode of transmission often leads to errors in measurement of RFI. Most standards for measurement are based on far-field measurements. One of the first steps in eliminating RFI is to determine its mode of transmission.

A third classification of RFI may be made by considering the types of sources. In general these include natural, inherent, and man-made sources. The natural sources include atmospheric disturbances, such as thunderstorms, solar disturbances, galactic disturbances, and precipitation static.

Thermal agitation and shot effect are inherent sources. All sources, other than natural and inherent, are lumped into one category of man-made interference. This broad category includes both desired and undesired products of communication and radar equipment, intentional interference, such as jamming, and disturbances caused by non-communication type electrical and electronic equipment. We shall center our interest on this last group of disturbance sources. A list of common sources of RFI includes:

(1) Combustion-engine electrical and ignition systems;
(2) Electrical transmission and distribution systems;
(3) Electrical power and distribution hardware;
(4) Machine tools such as lathes, presses, etc.;
(5) Portable electric hand tools such as electric drills, saws;
(6) Electric food-handling and processing equipment;
(7) Medical equipment such as diathermy and X-ray machines, whirl-pool baths, etc.
(8) Motor and generator commutators;
(9) Relays and switches;
(10) Fluorescent, neon, and mercury vapor lighting;
(11) Arc welders;
(12) Power rectifiers;
(13) Bearing friction;
(14) Battery chargers;
(15) Induction-heating apparatus;

(16) Sirens and vibrating gongs;

(17) Electrical railways, trolleys and buses;

(18) Household electrical appliances such as razors, food mixers, sewing machines, hair dryers, vacuum cleaners, electric blankets, irons, etc.

(19) Office machines, printing and lithographic equipment.

There are two general methods in which RFI may be generated; first, by variance of an electromagnetic force, and second, by variance of impedance in a circuit. These methods are explained by several examples in ref. (66). The variation in electromagnetic forces in rotating machinery is due to the relative motion of a set of conductors and a magnetic field. Ideally, the variation in an a-c machine is such that a pure sine wave voltage is generated, while in a d-c machine, the generated voltage at the output terminals is constant as the brushes slide on any one commutator segment and as they slide from one segment to the next. However, deviations from the ideal are present in both kinds of machines and variations from a pure sine wave and from a constant output always occur. Normally, d-c machines are more troublesome from the standpoint of RFI generation. The brushes in a d-c machine offer a good example of impedance variations which can cause RFI. The impedance between brushes and slip rings or a commutator depends upon the pressure applied and area of contact. Uneven wearing of

contact surfaces and machine vibrations cause uneven pressure variations and the area of contact is always changing. Thus, the impedance is always changing and a potential source of RFI exists. A switch is an even better example of changing impedance: When a switch is closed, the impedance is practically nothing; but when the switch is opened, the impedance approaches infinite values. Currents and voltages in the circuit must readjust themselves if there are reactive elements in the circuit, and this readjustment can not take place in zero time. However the voltage and current changes do take place very rapidly and lead to "transients" which are very closely related to pulses in their ability to generate RFI.

But one may ask, "Why worry about radio frequency interference? It's true that a buzz in my radio or flickering on my TV set is a nuisance, but is it worth so much concern just to eliminate such problems?" If these were the only problems caused by RFI, we would be fortunate. J. J. Krstansky and P. M. MacManamon cite in ref. (20) a case in which a missile being launched had its horizontal indicator thrown off by interference. The missile took an off-course heading and had to be destroyed. They cite another case in which a radar altimeter was disrupted by interference and gave an erroneous reading of 10,000 feet when the aircraft was actually at only 500 feet. In Chapter IX, cases are presented in which explosives were prematurely initiated by

RFI. Thus it can be seen that RFI can cause deadly consequences.

In ref. (62), it is pointed out that RFI problems are likely to grow with the passage of time. More foreign countries are developing their electronic capabilities, more space programs are being instituted which rely on the reception of very weak signals, and signal strengths and densities are increasing.

Radio frequency interference was present in our environment even before the advent of radio communications. But since it did not cause problems to man, he paid very little attention to it. In the early days of radio communication, the problem of RFI was often avoided mainly by choosing radio receiving sites which were geographically remote from populated areas. However, with the establishment of commercial broadcast stations in the 1920's, the necessity for protecting numerous receivers from RFI in populated areas arose.

In ref. (68) E. W. Allen lists some of the organizations and committees which have been interested in the control of RFI. The first of these was the National Electric Light Association Committee which began its RFI work in 1924. Chronologically, the following organizations in the United States have played a part in interference control work: The National Electrical Manufacturers Association Committee; EEI-NEMA-RMA Joint Coordination Committee; IEC International Special Committee on Radio Interference (CISPR); ASA Sectional Committee C-63; and SAE-RMA Vehicular Interference Subcommittee.

In Great Britain, the Post Office Electrical Engineers and the Electrical Research Association have worked long on the problems of RFI. The Department of Transport in Canada has also devoted much research to RFI control.

In Great Britain and Canada, an attempt has been made to control RFI through legislative steps. Some of the British Standards and Codes of Practice relating to RFI control are listed in ref. (83). They include regulations governing the limits of radio interference, methods of measurement, and suppression systems for household appliances, internal combustion engines, electro-medical and industrial equipment, and trolley buses. The main features of several Canadian standards are outlined in ref. (6).

In the United States, the Federal Communications Commission has the task of administering rules and regulations governing the use of the radio frequency spectrum. The parts of the FCC Rules and Regulations most applicable to RFI control are Part 15: Incidental and Restricted Radiation Devices and Part 18: Industrial, Scientific, and Medical Equipment. An incidental radiation device is defined in paragraph 15.4 (C) as

> a device that radiates radio frequency energy during the course of its operation although the device is not intentionally designed to generate radio frequency energy.

RFI limitations on such devices are very general and are given in paragraph 15.31 as follows:

> An incidental radiation device shall be operated

> so that the radio frequency energy that is radiated does not cause harmful interference. In the event that harmful interference is caused, the operator of the device shall promptly take steps to eliminate the harmful interference.

Regulations from Part 18 on industrial, scientific, and medical equipment are covered in later chapters.

Although they do not have the effect of law, various military standards and specifications have played an important role in making many manufacturers conscious of RFI problems. A partial listing of Military Standards and Specifications applicable to RFI measurement and control may be found in Appendix B.

The establishment of the Electronic Compatability Analysis Center, Annapolis, Maryland, is one indication of the attention that the Department of Defense is giving to RFI control. In addition to this joint effort, each of the military services has programs underway which are aimed at reducing radio frequency interference. The U. S. Air Force program is directed by Ground Electronics Engineering-Installations Agency (GEEIA) and is outlined in ref. (26). The Bureau of Ships is responsible for the U. S. Navy RADHAZ (Radiation Hazards Program).

No discussion of RFI is complete today without mention of the Institute of Electrical and Electronics Engineers Professional Group on Radio Frequency Interference. The Conference Proceedings and Transactions of this organization are a very good source on the current thinking of both industry and government officials on RFI.

In the succeeding chapters, some of the more common sources of RFI will be treated in greater detail. Specific methods by which interference is generated and how it can be measured and suppressed will be discussed.

(Note on bibliography for this chapter: Refs. (1), (4), (34), and (71) are bibliographies which cover RFI from all types of sources. Ref. (36) also contains an extensive bibliography. Ref. (27) is the most complete work on RFI that could be found in our search. Articles covering broad aspects of RFI which could not appropriately be included in one of the following chapters are also included in this bibliography.)

CHAPTER II
BIBLIOGRAPHY AND ABSTRACTS

1. C. E. Blakely, R. N. Bailey, H. H. Jenkins, W. M. Rogers, E. W. Wood, R. F. Ficcki, Bibliography on Radio Frequency Interference, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, RFI-4, No. 1, Feb. 1962.

   "This bibliography has been compiled from two separate bibliographies, one of which was prepared at the Georgia Institute of Technology in the course of a research program conducted for the Department of the Army and the other was prepared at the Radio Corporation of America as a consequence of investigations carried out on a large systems complex."

2. A. C. Warren, Broadcast Interference Investigations-'Post Office Radio Service', POST OFFICE ELECTRICAL ENGINEERS JOURNAL, Vol. 28, pp. 23-26, April 1935.

3. J. E. Foster, Causes and Eliminations of Radio Interference, C. W. Nelson Company, South Braintree, Mass., 1937.

4. A. E. Tooke and H. F. Church, Classified Bibliography of Man-Made Radio Interference and Associated Measurements, British Electrical and Allied Industries Research Association Report M/T 22, 1934.

   Included are 216 references on radio interference and 66 on field strength measurements.

5. L. Blok, Combating Radio Interference, PHILIPS TECHNICAL REVIEW, Vol. 4, pp. 237-243, Aug. 1939.

   "In this article it is shown how radio interferences can be suppressed in the neighborhood of the source of interference, and how interferences can be prevented from entering the mains. The method is further discussed of combating radio interference at the receiving set."

6. G. C. W. Browne, Control of Radio Interference in Canada, Institute of Radio Engineers Convention Record, Part 7, (Symposium on Spurious Radiation), pp. 130-137, 1955.

   A brief history of the inception of RFI control regulations and the work of the Department of Transport in Canada is given by the author. Some of the Canadian Interference Standards are briefly outlined.

7. Design Techniques for Interference-Free Operation of Airborne Electronic Equipment, Frederick Research

Corporation, 1952, (TIP G U22993).

"Design techniques are presented which may be used as a guide by the aircraft and equipment designer for the interference free operation of airborne electronic equipment. A discussion is given of the basic theory of interference and the theory is applied to illustrative components and system problems. Applicable interference specifications are discussed together with methods of measurement and acceptable interference test sets. A section is devoted to precipitation static and the techniques useful for its suppression."

8. P. J. Klass, DOD Group Studies Emitter Interference, AVIATION WEEK, Vol. 77, pp. 55-56, July 23, 1962.

9. C. D. LaFond, DOD Zeroes in on R-F Interference, MISSILES AND ROCKETS, Vol. 9, pp. 27-28, Dec. 4, 1961.

The reasoning behind the establishment of and the tasks of the Electronic Compatability Analysis Center are presented.

10. C. S. Vasaka, The Effect of Radio Interference in Airborne Electronics, Naval Air Development Center, Johnsville, Pa., Feb. 1, 1955, (AD-60 653).

This report outlines the origins, types, and sources of radio interference that may be present in an aircraft. Corrective actions that may be taken at the source and at a receiver are outlined. Applicable Military Specifications and allowable interference levels are listed along with acceptable measuring instruments.

11. R. T. Keyes, Electrical Fields and Electromagnetic Radiation From Chemical Explosions, Institute of Metals and Explosives Research, Univ. of Utah, Salt Lake City, March 19, 1959, (AD-216 691).

"Electrical fields and electromagnetic radiation generated by chemical detonations of charges ranging in size from 10g to roughly 25 kg were investigated over a frequency range extending from a few cycles per second to 500 mc. The electrical energy in all cases was found to cover a broad band of frequencies with the largest potentials occurring in a frequency range below a few hundred cycles per second. Little of the low frequency signals were radiated. Megacycle range signals (predominately radiation) were found to occur in the form of short random bursts.

A non-reproducible delay, the order of several hundred microseconds, was found to exist between the time of detonation and the appearance of the first bursts of radiation. The electrical potentials of the expanding explosion products were estimated, and for a 552g 50/50 pentolite charge the maximum value was determined to be 18,000 v. For bare charges this quantity was considered to vary roughly in direct proportion to the charge weight. Experiments are described which were performed to ascertain the mechanism whereby the electrical fields and EM radiation are generated by chemical detonations, and a model is proposed."

12. J. C. Coe, Electrical Interference, INSTRUMENTS AND AUTOMATION, Vol. 31, pp. 1046-1049, June 1958.

The author points out the methods by which errors can be induced in instruments which are used near control and power circuits. The causes of interference and types of remedial action are discussed, including (1) reducing the cause of interference, (2) neutralizing the means by which it is transferred, and (3) applying corrective action after it is transferred.

13. Electrical Interference With Broadcasting, ENGINEER, Vol. 162, pp. 89-90, July 24, 1936.

14. Electrical Interference With Broadcasting, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 79, pp. 206-212, Aug. 1936.

This article is a report of a committee of the IEE that was set up to study all phases of radio interference. The report includes a list of all sources of interference studied, measurement methods, suppression costs, and regulations governing interference generation. Recommendations are given for establishing a commission to control RFI. Thirty-seven references are included.

15. Howe, Electrical Interference With Broadcasting Reception, WIRELESS ENGINEER, Vol. 10, pp. 645-647, Dec. 1933.

16. A. J. Gill, S. Whitehead, Electrical Interference With Radio Reception, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol 83, pp. 345-386, Sept. 1938.

"The paper describes the method of assessment of the interference to radio reception from electrical equipment, and determines the level to which such

interference must be reduced to permit satisfactory service. The methods of achieving this result are described for the various classes of interfering equipment. Although mainly directed towards the protection of broadcast reception, the principles described apply equally to the radio communication services."

17. J. E. Curran, Electrical Noise Control, ELECTRO-TECHNOLOGY, Vol 68, pp. 117-124, Dec. 1961.

    The author discusses some of the ways in which electrical noise can enter a computer system. He also shows circuits with applications of filters, noise-suppression diodes, surge-suppression diodes, feed-through capacitors, r-f screening, and proper grounding on motor power supplies.

18. John T. Egli, Electromagnetic Interference and Vulnerability Reduction, Army Signal Research and Development Laboratory, Fort Monmouth, N. J., 1960,(AD-241 740).

    "Interference and vulnerability, the first signifying a mutual or unintentional interference, and the second signifying an intentional interference are omnipresent disturbances which must be reduced to permit tactics of the military to be consummated without extraneous impairment. In the research and development area of electromagnetic interference and vulnerability reduction, three important phases are essential to achieve reduction: (1) theoretical analysis, (2) design criteria, and (3) instrumentation and measurements. A research and development organization capable of handling these three important phases has been established at the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J."

19. Electronic Interference Limits Spectrum Use, U. S. BUREAU OF SHIPS JOURNAL, Vol. 7, pg. 38, July 1958.

    The problem of interference in military electronics is outlined briefly. Crowding of the electromagnetic spectrum is also discussed.

20. J. J. Krstansky, P. M. MacManamon, Electromagnetic Compatibility, SPACE/AERONAUTICS, Vol. 38, pp. 66-71 July; pp. 62-68 August; pp. 68-75 October, 1962.

    This series of three articles outlines the general goals and basic practical requirements of compatibility control, analyzes the nature of natural and

and man-made interference, reviews RFI instrumentation problems, and advocates design attention to shielding, bonding, and filtering.

21. Cletus M. Wiley, Electromagnetic Compatibility Analysis Center Ready to Start Battle with RFI, ELECTRONICS, Vol. 34, pp. 28-9, Nov. 24, 1961.

The author gives brief highlights of the Seventh Conference on Radio Interference Reduction and Electromagnetic Compatibility. Included is a summary of the type work to be undertaken at the Electromagnetic Compatibility Analysis Center at Annapolis, Maryland. Other items mentioned are a transistorized r-f field intensity meter and a coherent memory filter.

22. W. W. Fain, C. M. Crain, W. C. Duesterhoeft, Electromagnetic Noise and Propagation Observations in Vicinity of Nuclear Reactor, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON ANTENNAS AND PROPAGATION, AP-6, pp. 286-288, July 1958.

The article describes electromagnetic and propagation measurements that were made in the vicinity of a nuclear reactor. Measurements made showed no significant electromagnetic noise generated by reactor radiation.

23. E. J. Coriell, Elimination of R. F. Interference in Audio Systems, RADIO AND TV NEWS, No. 51, pp. 56-57, June 1954; No. 52, pp. 44-45, July 1954.

The author points out some sources of RFI that may cause problems in an audio system. Suppression techniques are described for some of the sources. If suppression cannot be achieved at the source, the author proposes the use of shielding, filtering, and grounding techniques on the audio equipment.

24. C. V. Aggers, Eliminating Radio Interference, ELECTRIC JOURNAL, Vol. 34, pp. 331-334, Aug. 1937.

This article is generally concerned with the description of a field intensity meter that was developed to measure RFI. Procedures for determining the interference influence of high- and low-voltage equipments are given. The importance of having an efficient antenna is stressed.

25. E. W. Allen, H. Garlan, FCC Controls Man-Made RFI, ELECTRONIC INDUSTRIES, Vol. 19, pp. 86-92, Oct. 1960.

26. L. A. Yarbrough, J. W. Worthington, Fire Prevention or Fire Fighting, INSTITUTE OF RADIO ENGINEERS INTERNATIONAL CONVENTION RECORD, Vol. 8, pp. 54-64, (pt. 8), 1960.

This paper presents the function, organization, interference responsibilities, capabilities, and standards program of the U. S. Air Force Ground Electronics Engineering-Installation Agency (GEEIA). A list of Air Force publications applicable to RFI is included.

27. Handbook on Radio Frequency Interference, Frederick Research Corporation, 1962.

"This Handbook is addressed to system planners, designers, field engineers, and other technical people who must deal with compatability problems in communication-electronic systems. RFI theory, prediction procedures, measurement techniques, instruments, specifications and design are covered in the four Handbook volumes listed below:

Vol. I Fundamentals of Electromagnetic Interference
Vol. II Electromagnetic Interference Prediction and Measurement
Vol. III Methods of Electromagnetic Interference-Free Design and Interference Suppression
Vol. IV Utilization of the Electromagnetic Spectrum"

28. Leonard W. Thomas, Handling Radio Interference, U. S. BUREAU OF SHIPS JOURNAL, Vol. 1, pp. 31-34, Feb. 1953.

The history of Navy interest in RFI control is given. The role that BuShips plays in the Interference Reduction program is outlined. The article also lists field intensity meters which can be used.

29. F. H. Frantz, Sr., Interference -- Causes, Remedies and Location, RADIO-ELECTRONICS, Vol. 31, pp. 98-101, July 1960.

The author discusses the common causes of interference and remedies which can be applied at a receiver. As this article is written for the layman, the author suggests the use of a battery powered broadcast receiver with a directional antenna for locating interference sources. He also suggests simple remedies for small electric motors, switches, relays, thermostats, and fluorescent lamps.

30. Interference Problem Attacked by Defense, AVIATION WEEK, Vol. 72, pg. 78, June 20, 1960.

Three steps the Defense Department is taking against RFI are outlined. They are (1) establishment of the Electromagnetic Analysis Center, a clearing house for spectrum signature information, (2) issuance of new measurement standards, and (3) establishment of minimum design standards in regard to bandwidth limits, frequency stability, average radiation power levels for cross-modulation products, susceptibility limits, and required antenna side-lobe suppression.

31. Interference Source Discovered, ELECTRONICS, Vol. 9, pg. 19, Feb. 1936.

This article relates how interference in the range of eight to 28 mc was traced to short-wave therapeutic apparatus.

32. Interference Studies, Institute for Cooperative Research, Final Report Task 1, Vol. 1 of 2, April 1958 (AD-148 812).

33. Introductory Background Theory for Electromagnetic Interference Analysis, Naval Civil Engineering Laboratory, Tech. Rpt. N-344, Aug. 1958.

"The problem is essentially that of a source of radio interference that can either be radiated directly, or conducted down the line and re-radiated along all or parts of the line. Theoretically to understand this phenomenon, it is necessary to have background in the propagation of waves and antenna theory (the line acts as an antenna) which includes a knowledge of electromagnetic theory, itself based on partial differential equations and vector analysis. This report represents a summary of the essential parts of the theory to give the necessary initial background. Prior contact with the elements of the theory is assumed and although many of the relationships have been explored fully, the more rigid mathematical proofs are not stated but referenced to standard books on the subject."

34. G. I. Chandler, Introductory Bibliography on Electrical Interference, Autonetics, Downey, Calif., July 29, 1960, (AD-241 743).

"In this bibliography on electrical interference, an attempt has been made to provide references on general noise theory as well as specific information relating to D-C motor noise generation and

suppression techniques. The literature search includes publications from 1931 through 1960. There are 118 references divided into five groups by subject, arranged in alphabetical order and followed by an author index."

35. Isn't RFI Your Problem, U. S. BUREAU OF SHIPS JOURNAL, Vol. 7, pg. 33, June 1958.

    This editorial type article takes manufacturers to task for not incorporating better RFI control into equipment. Some of the problems that RFI causes to missiles, aircraft, and communications are briefly mentioned.

36. L. Castriota, Microwave Interference Investigations for the Frequency Range 1000 - 40,000 MC/Sec., Polytechnic Institute of Brooklyn, April 1952.

    Although this report is mainly concerned with interference from radar sources, it is included within this bibliography because it contains a bibliography of 237 references that cover theory, measurement, and suppression of man-made noise from both communication and non-communication equipment.

37. M. L. Muhleman, Mysterious Interference: The Shadow, SCIENTIFIC AMERICAN, Vol. 154, pg. 100, Feb. 1936.

38. New Way to Beat R-F Radiation, FACTORY MANAGEMENT, Vol. 113, pg. 145, November 1955.

39. I. I. K. Pauliny-toth, J. R. Shakeshaft, A Note on Radio Interference At a Frequency of 408 Mc/s, ELECTRONIC ENGINEERING, Vol. 34, pg. 488, July 1962.

40. R. P. Hareland, The Prevention and Elimination of Certain Electrical Interference in Missiles, General Electric Company, June 1953, (AD-19 117).

    "This report is a preliminary examination of the problems of preventing and eliminating electrical and electromagnetic interference to missiles. It was prepared to assist in the formulation of a philosophy of approach to the basic problem."

41. The Problem of Radio Interference, WELDING ENGINEER, Vol. 34, pp. 33-37, 48, Feb. 1949.

42. Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 7-8, 1954, (AD-76 686)

Proceedings of the Third Conference on Radio Interference Reduction, Held at the Museum of Science and Industry, Chicago, Illinois, Armour Research Foundation, Feb. 26-27, 1957, (AD-234 211).

Proceedings of the Fourth Conference on Radio Interference Reduction and Electronic Compatibility, Held at the Museum of Science and Industry, Chicago, Illinois, Armour Research Foundation, Oct. 1-2, 1958, (AD-234 212).

Proceedings of the Fifth Conference on Radio Interference Reduction and Electronic Compatibility, Held at the Museum of Science and Industry, Chicago, Illinois, Armour Research Foundation, Oct. 6, 7, and 8, 1959, (AD-235 099).

Proceedings of the Sixth Conference on Radio Interference Reduction and Electronic Compatibility, Held at the Museum of Science and Industry, Chicago, Illinois, Armour Research Foundation, Oct. 4, 5, and 6, 1960, (AD-253 015).

Proceedings of the Seventh Conference on Radio Interference Reduction and Electronic Compatibility, Held at Grover M. Hermann Hall, Illinois Institute of Technology, Chicago, Illinois, Armour Research Foundation, Nov. 7, 8, and 9, 1961, (AD-276 205).

43. Proceedings of the Unclassified Sessions of Symposium on Electromagnetic Interference, 19-21 November 1957, at the Hotel Berkeley-Carteret, Asbury Park, New Jersey, Army Signal Research and Development Laboratory, Fort Monmouth, N. J., June 15, 1958, (AD-203 592).

44. L. Valich, R. B. Schulz, Propagation Consideration in RFI, ELECTRONIC INDUSTRIES, Vol. 19, pp. 80-86, Dec. 1960.

45. RF Interference Control Handbook, Howard W. Sams and Company Inc., Indianapolis, Indiana, 1963.

This book contains chapters on the theory of RF interference, interference measurements, interference measuring equipment, measurement problems, electrical circuit noise, semi-conductor circuit interference, switches and contactors, suppression techniques, suppression in rotating machinery, suppression in ignition systems, and suppression at the system level.

46. Jean Jolkovski, Radio Frequency Interference Report, 1963-1970, SIGNAL, Vol. 17, pg. 42, Jan. 1963.

The author points out that in the next seven years, RFI problems will grow unless definite steps are taken immediately to control them. The importance of taking such action is stressed, and certain actions which can be undertaken are mentioned.

47. L Blok, Radio Interference, PHILIPS TECHNICAL REVIEW, Vol. 3, pp. 235-240, Aug. 1938.

48. N. R. Bligh, R. F. Procter, Radio Interference, GENERAL ELECTRIC COMPANY JOURNAL, Vol. 11, pp. 55-65, Feb. 1940.

49. Radio Interference, WIRELESS WORLD, Vol. 55, pp. 149-153, April 1949.

50. D. A. Thorn, Radio Interference. I. Introduction, POST OFFICE ELECTRICAL ENGINEER'S JOURNAL, Vol. 50, pp. 226-227, Jan. 1958.

G.A.C.R. Britton, Radio Interference. II. The Post Office Radio Interference Service, POST OFFICE ELECTRICAL ENGINEER'S JOURNAL, Vol. 50, pp. 227-230, Jan. 1958.

51. C. W. Sowton, Radio Interference. IV. The Control of Radio Interference, POST OFFICE ELECTRICAL ENGINEER'S JOURNAL, Vol 52, pp. 43-46, April 1959.

52. Radio Interference, WIRELESS WORLD, Vol. 68, pg. 514, Oct. 1962.

This article identifies sources of interference found in England during 1961. Eighty-six thousand complaints were investigated and the article tabulates the numbers of complaints according to source of RFI.

53. Radio Interference Conference, ELECTRICAL REVIEW, Vol. 153, pp. 1159-1160, Nov. 20, 1953.

This article briefly reviews the conference of the Special Committee on Radio Interference (CISPR). The committee sought agreement on three specific problems, namely: the limits which should be imposed on the production of "man-made" interference; methods of measuring interference and the type of equipment to be used, so that measurements made in one country might be related to those made in other countries; and safety considerations involved in the use of suppression devices on electrical appliances and machinery.

54. C. F. Maylott, Radio Interference Control, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, (Pt. 1 -- Communication and Electronics), Vol. 72, pp. 401-413, Jan. 1953.

This article discusses radio interference sources, effects on radio receivers and methods of control. Interference caused by engines, electric systems and ignitions are briefly reviewed. The following areas in government radio interference specifications are covered: suppression covered and not covered by subsidiary specifications, optional and mandatory design features, qualification and production test conditions, test equipment, methods and limits. Recommended practices for achieving and maintaining radio interference control are listed.

55. A. L. Albin, J. McManus, Radio Interference Control in Aircraft, TELE-TECH AND ELECTRONIC INDUSTRIES, Vol. 14, pp. 76-77, Nov. 1955.

The authors describe some of the sources of interference that are found in aircraft. The general methods proposed for controlling interference are filtering, isolation of components, shielding, and selection of components with fewer RFI characteristics. Measurement techniques and applicable government specifications are also mentioned.

56. F. J. Nichols, Radio Interference Control of Semiconductor Circuitry, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 487-510, Oct. 1958, (AD-234 212).

This paper summarizes the radio interference and susceptibility measurements for several transistor circuits, typical diode circuits, and circuits using both transistors and diodes. The characteristics of the RFI that can be generated are discussed. Steps that can be taken to reduce RFI are also discussed.

57. D. M. Hill, Radio Interference Evaluation Tests XB-62B, GM 11114 (N-3275), Northrop Aircraft, Inc., Nov. 1954, (AD-54 025).

This report contains results of radio interference tests on the subject missile. The purpose of the tests was to determine the existence and degree of radio interference, and the amount of interaction between the missile sub-systems.

58. J. O. Merriman, Radio Interference from Electrical Apparatus and Systems, Department of Transport, Ottawa, Ontario, Canada, 1954.

This book is essentially a handbook describing briefly sources of interference and methods of controlling such sources primarily through the techniques of suppression and shielding. Included, however, are general discussions of radio noise and interference, methods of conducting interference investigations and of making quantitative measurements, and the principles of suppression. There are also detailed chapters dealing with the origin and specific methods of suppression of noise on power and distribution lines, high-voltage equipment, electric railway systems, wire communication systems. commutator motors and generators, etc. The concluding chapters discuss interference in ship and aircraft, and also radio interference standards in legislation.

59. R. E. Shewmaker, R. F. Interference in Extreme Environments, ENVIRONMENTAL QUARTERLY, Vol. 6, pp. 14-15, Jan. 1960.

"Specimen of broad band RF noise characteristics was subjected to simulated environments of elevated temperature and humidity, low temperature and altitude, and elevated temperature and altitude representing environments encountered in preflight or flight of XQ-4 supersonic target drone system; results indicated interference characteristics, as related to resonance and maximum noise levels vs. frequency, have shown negligible change resulting from exposure to environment."

60. S. F. Pearce, Radio Interference in Ships, ENGINEER, Vol. 185, pp. 261-263, March 12, 1948.

"Details of experiments on interference conducted aboard five merchant ships are presented. The coupling between supply wiring and the antennas, measured at several places on the ship was -70±13db for several ships. For good steel ships this becomes -79.5±10db. For wood ships the values are much lower and range from -50 to -90 db. The statement is made that the coupling is much lower on ships than for domestic installations. Results indicate that suppression on the ancillary electrical equipment may be reduced to a negligible amount if suitable precautions are taken. High-quality reception should be possible when machines

of rf terminal voltage as high as 5 mv are in operation."

61. V. Jensen, Radio Interference in VHF Range, TELETEKNIK, Vol. 3, pp. 1-17, Jan. 1959.

62. Radio Interference Problems to Worsen, MISSILES AND ROCKETS, Vol. 11, pg. 27, Oct. 15, 1962.

This article points out that, because of the trend toward increasing signal densities and strengths, rapidly expanding space programs, and growing capabilities of foreign countries, the RFI problem is growing. The problems that are caused by RFI and some steps being taken to combat it are mentioned.

63. Leonard W. Thomas, Radio Interference to Missiles - Recommendations for Reduction, U. S. BUREAU OF SHIPS JOURNAL, Vol. 6, pp. 32-35, Dec. 1957.

RFI control techniques which are presented as possible solutions are filtering of power circuits, shielding of low-level high-impedance leads, and the use of low pass, high pass, or band pass filters on radio frequency inputs. The author also advocates establishing uniform measurement techniques.

64. R. L. Haskins, A. S. Zamanakos, Radio Interference Sources Grouped, U. S. BUREAU OF SHIPS JOURNAL, Vol. 1, pg. 24, June 1952.

The authors group electronic interference sources on ships in three groups: electronic, electrical, and interior-communications sources. Of 217 complaints, 85.5% were caused by electronic sources, 10.1% from electrical equipment, and 1.4% from interior-communications.

65. Radio Interference Studies, Burroughs Corporation, Feb. 1953, (AD-35 200).

66. Radio Interference Suppression Techniques - A Guide for Manufacturers. Coles Signal Laboratories, Signal Corps Engineering Laboratory, Nov. 1953, (AD-21 192).

"This manual deals principally with approved suppression systems and components and their application for all kinds of equipment used by the Armed Forces. In addition to the main body of the manual dealing with suppression systems and components

and their applications, there are two chapters on test, testing procedures, and specifications, and a concluding chapter on the fundamentals of radio interference and its suppression. The chapters on tests and specifications explain and describe the testing procedures in detail The concluding theoretical part is designed to give the reader an appreciation of the problems and an insight into the reasons behind the suppression procedures."

67. Radio Interference Transients Investigation - I, Minnesota Univ. and U. S. AAF, Air Technical Service Command, March 1946, (PB L 85953).

Radio Interference Transients Investigation - II, Minnesota Univ. and U. S. AAF, Air Technical Service Command, June 1946, (PB L 85954).

"The objectives of this work are directed towards a more complete understanding of the radio interference problem by approaching it from the transient point of view through the use of high-speed oscillographic techniques."

68. Donald Howard Menzel, Radio Noise Spectrum, Harvard University Press, Cambridge, Mass., 1960.

The bulk of this book is devoted to noise from natural sources. However chapter one is devoted to man-made noise The author outlines the history of the development of committees interested in RFI. The part of the FCC in RFI control is mentioned and it is pointed out that many cities have enacted ordinances directed toward the control of radio noise.

69. C. M. Salati, Recent Developments in RF Interference, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RFI, Vol. RFI-4, pp. 24-33, May 1962.

"Present trends in design of transmitters, receivers, and antennas for use in communications and radar are reviewed to assess their impact on interference, interference measurement techniques, shielding and prediction methods. 21 refs."

70. E. S. Darlington, Reducing SW Interference, RADIO NEWS, Vol. 18, pg. 473, July 1937.

71. L. F. Roehman, References on Radio Interference, (Compiled by L. F. Roehman), ELECTRONICS, Vol. 11, pg. 32, Oct. 1938.

This bibliography contains 69 references. General areas covered are regulations, measuring techniques, aerials, and interference from insulators and other sources.

72. T. W. Bennington, Short-Wave Disturbances, WIRELESS WORLD, Vol. 48, pp. 79-82, April 1942.

73. Signal Corps Check RFI at Fort Huachuca, Arizona, ELECTRONIC INDUSTRIES, Vol. 19, pp. 110-111, Dec. 1960.

74. Siting Criteria for HF Communications Centers, National Bureau of Standards, Boulder, Colorado, NBS Technical Note No. 139, April 1962, (AD-281 052).

75. Sources of Interference, compiled by British Post Office Interference Investigation Service, WIRELESS WORLD, Vol. 57, pg. 468, Nov. 1951.

76. P. M. Ross, Sources of Radio Interference and How to Eliminate Them, ELECTRIC LIGHT AND POWER, Vol. 17, pp. 38-39, Sept. 1939.

77. Stopping RFI Improves Standards, U. S. BUREAU OF SHIPS JOURNAL, Vol. 5, pp. 29-30, March 1957.

Preventing RFI through design is stressed. Longer contact and switch life, smoother and more efficient relay and motor operation, longer bearing life in motors, and general lower over-all maintenance costs on machines and equipment can be achieved with proper RFI controls.

78. Suppression of Radio Interference, ELECTRICAL REVIEW, Vol. 159, pp. 310-311, Aug. 17, 1956.

This brief article relates the topics discussed at the fifth plenary session of the International Special Committee on Radio Interference (C.I.S.P.R.) in Brussels in July 1956. The three main topics were limits of interference and methods of control, measurement of radio interference, and safety aspects of suppression techniques.

79. S. Whitehead, Tentative Statistical Study of Domestic Radio Interference, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Part 3, Vol. 90, pp. 181-192, Dec. 1943.

80. F. H. Hamm, 3700 Sleuths, ELECTRONICS, Vol 9, pp. 11 and 38, Oct. 1936.

This article is a description of a unique effort

by the citizens of a community to ferret out the sources of radio interference.

81. C. R. Billheimer, Timely Consideration of Interference Control, U. S. BUREAU OF SHIPS JOURNAL, Vol. 7, pg.31, May 1958.

The importance of "designing-out" RFI is stressed in this short article. The author points out that supply contractors are responsible for ensuring their equipment is properly suppressed.

82. F. West, What Causes Interference on Your Radio, RADIO TIMES, Vol. 4, pp. 8-9, Sept. 16, 1949.

83. Work of ERA on Radio Interference Suppression, ENGINEER, Vol. 188, pg. 493, Oct. 28, 1949.

This article reviews the work of the British Electrical and Allied Industries Research Association on radio interference from electrical appliances and motor vehicles. A list of British Standards and Codes of Practice which have been generated by ERA work are given.

CHAPTER III

IGNITION INTERFERENCE

An ignition system is designed to produce a spark to ignite a compressed mixture of fuel and air inside the cylinder of an internal combustion engine. Ignition systems may be divided into two general categories--battery and magneto. Ignition systems are one of the major sources of radio interference because of the steep transient waves developed immediately after the firing of the plug. This impulse consists of a fundamental and a series of harmonics. Radiated interference can be prevented by shielding the entire system in a metallic container. Resistive components placed in series with the high tension lead of the distributor are also utilized to reduce the level of interference. The use of this type of suppression must be compatible with the performance requirements of the ignition system.

Historically the requirement for shielding ignition systems was recognized in the late 1920's. Diamond and Gardner, of the National Bureau of Standards, in ref. (26), described techniques for shielding aircraft ignition systems. This largely consisted of confining the electric fields of the ignition system so that the interference would not be set up in the radio receiver circuits. The chief problem was to electrically and mechanically design the shield so as to not seriously affect the performance of the engine ignition system.

One of the earliest reports on ignition interference, ref. (21), generated by automobiles was written by L. F. Curtis, in 1932. He identified the location of interference as:

(a) at the spark plugs;

(b) at the high tension distributor or at poorly connected leads in its circuit;

(c) at the low tension interruptor; or

(d) at the generator brushes.

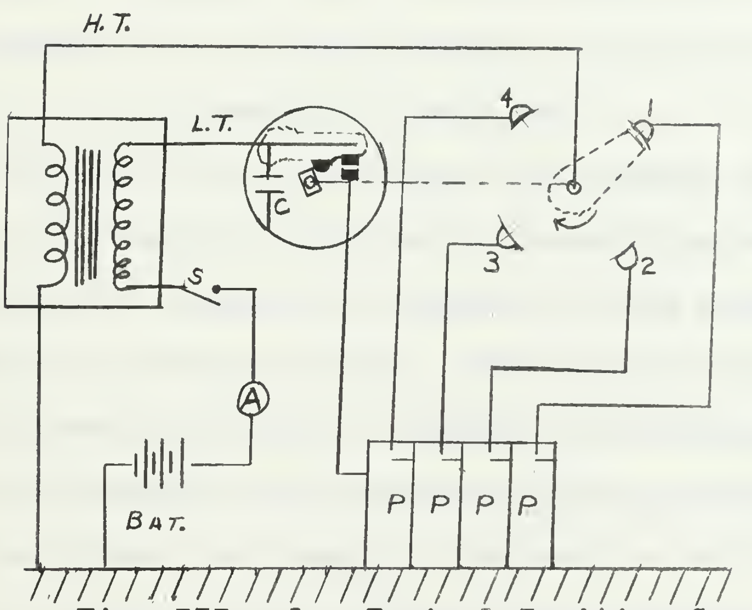

Fig. III - 1 Typical Ignition System

The successive periods in the ignition cycle are as follows:

(a) Interruptor open -- no current;

(b) Interruptor closed -- current building up:

(c) Contacts start to open -- primary current causes arc or spark at contacts;

(d) Contact spark extinguished -- start of low frequency oscillation -- common secondary cable rises in voltage;

(e) Rotor gap voltage gradient allows breakdown -- individual plug cable rises in voltage;

(f) Plug gap breaks down -- secondary ignition current flows;

(g) Ignition current ceases -- oscillatory primary energy finally dissipated.

Curtis suggests that the most effective means of reducing radiation is to insert series resistance as close as possible to the sparking electrodes.

In 1937, Peters, Blackburn, and Hannon of the National Bureau of Standards published a research paper, ref. (20), detailing the electrical character of the spark discharge of automotive ignition systems. They measured the current in the discharge utilizing a cathode ray oscillograph. From the oscillograms they measured frequency, decrement, effective resistance and energy. Frequencies of 5 to 10 mc with crest currents of 50 to 80 amps were measured. Results indicated that radiated frequencies in excess of 200 mc were probable. The "spark" occurring in the secondary circuit of a spark generator on interrupting the primary current usually consists of a number of separate discharges, each of which may consist of a capacitive and inductive component. In each discharge the decay of the current in the inductive

component is followed by the rapid rise of resistance of the gap, whereupon the capacitance is again charged to such voltage that the discharge is repeated. The spark ends when there is no longer sufficient energy in the secondary winding to charge the capacitance to the breakdown voltage. Scholz and Faust, in ref. (99), in 1939 verified earlier findings that the radiation from ignition systems could not be suppressed by series coils and shunt capacitors. The most effective means was the use of distributed resistance leads.

In 1940, R. George described in ref. (29) measurement of the peak field strength of motorcar ignition in the VHF band and higher. He found that considerable interference was present at 450 mc and higher and polarization could take all forms. He indicated that at higher frequencies the metal sections of the car and the ignition leads are more comparable in size with short wavelengths and are less effective shields and more effective radiators. Therefore although r-f power falls off considerably with increasing frequency it can still produce substantial field strength.

In 1942 Randolph indicated in ref. (3) that the shielding structure must meet exacting electrical requirements. All parts of the structure must be maintained at ground potential. Proper "grounding" means very low resistance joints and connections and grounding at frequent intervals. Interference becomes marked if the resistance across a joint

or at a grounding point is over 0.002 ohms. Dean, in ref. (37) on the effects of ignition noise on UHF and VHF reception, illustrates the effects of various types of shielding on the spark discharge wave train. If the secondary circuit is shielded the connecting line between the generator and the spark gap becomes a coaxial transmission line. This addition of shielding causes reflections to be set up in the line, resulting in high frequency modulation envelopes on the fundamental discharge wave. If a second line is included in the same coaxial shield and a separate source is furnished to drive it through a second spark gap, the high frequency component of the discharge will be further increased in amplitude and duration. A. E. Teachman. in ref. (74), describes a series of tests on aircraft ignition interference. He indicated that the principal radiated noise lies above 10 mc and that resistance cable is most effective in the same frequency range, yielding a 24 db reduction in the range from 10 to 150 mc. Tests also indicated that a lumped resistance at the spark plug had little effect on the radio noise intensity. It was further emphasized that since the maximum interference from the ignition system is in the VHF range and that joint leakage increases with frequency, the problem of joints in shielding is more serious than the leakage due to penetration. In 1946, Eaglesfield, in ref. (50), introduced the theory of considering the spark plug as a switch and then calculating its current and radiated field

considering the inductance of the ignition lead. This concept resulted in the following equation for an equivalent electric field:

$$E_{EQUIV} = \frac{\mu}{4\pi C} \quad \frac{A V B}{L R} \quad \text{Volts/METER}$$

c = velocity of propagation

A = area of inductive loop

V = breakdown voltage

B = bandwidth of receiver in cps

L = inductance of loop

R = distance in meters from source

The values obtained compared favorably with the experimental results obtained by George and reported in ref. (29). Eaglesfield further determined experimentally that each normal spark gave rise to a train of pulses in the receiver output averaging 15 pulses per train. In 1949, Pressey and Ashwell reported in ref. (60) on the extension of the measurement of ignition interference to 650 mc utilizing wide band (2.5 mc bandwidth) measuring equipment. They confirmed the existence of the train of pulses but noted that the secondary train was effectively suppressed when resistance was used in the ignition circuit. Their experimental results showed no falling off in the level of interference with an increase in frequency, but instead showed a tendency to rise. In the same year Nethercot, in ref. (11), advanced an alternate theory on the radiation from an ignition system. He

theorized that the wideband continuous radiation from the ignition circuit is due to travelling waves set up in the high tension ignition wires when the distributor and spark gap break down. The current through the spark plug gap consists of a series of very steep-fronted steps, the intervals between which are determined by the time the waves take to travel twice the length of the H. T. cables. In 1951, Eaglesfield, in ref. (12), extended his previously advanced theory on ignition radiation to include resonances in the ignition system and the introduction of suppressing devices. He introduced an additional element Z in series with L. Z consists of the capacitance of the ignition lead and r, the lumped resistances at the spark plug and coil. He determined the suppression ratio, i.e. $\left|\frac{j\omega L + Z(j\omega)}{j\omega L}\right|$ to be as follows:

r at spark plug (r_1)

$$\text{Suppression Ratio} = \sqrt{1 + \left(\frac{r_1}{\omega L}\right)^2 \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^2}$$

r at spark coil (r_2)

$$\text{Suppression Ratio} = \sqrt{\frac{1 + \left(\frac{r_2}{\omega L}\right)^2 \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^2}{1 + (\omega C r_2)^2}}$$

$r_1 = r_2 = r$

$$\text{Suppression Ratio} = \sqrt{1 + \left(\frac{r_2}{\omega L}\right)^2 \left[2 - \left(\frac{\omega}{\omega_0}\right)^2\right]^2}$$

In each case $\omega_0^2 LC = 1$

Comparison with the published measurements by George, and by Pressey and Ashwell, showed the same general shape for the calculated and measured curves. In 1954, the Naval Air Test Center, Patuxent, Maryland, conducted tests on the effectiveness of distributed resistance and lumped resistors in the ignition system. It was reported in ref. (96) that the field about an 8000 ohm/ft. distributed resistance cable diminished rapidly along the cable and concluded that its effectiveness as a suppressor of ignition interference depends upon the amount of electrical shielding at the spark plug and along the first few inches of the cable attached to the spark plug. In the case of resistance lumped into the spark plug, its advantage is that it reduces the interference before it is coupled to the ignition cable. However, the remaining interference is radiated by the standard ignition cable which acts as an antenna.

In 1959, a series of tests, reported in ref. (65), were undertaken comparing American, German and British measuring equipment, techniques and limits as applied to radio interference from ignition systems. Tests were made on various vehicles, taking both peak and quasi-peak values, horizontally and vertically polarized. Results showed consistency of agreement between the American, German and British sets. The paper also discussed the difficult problem of obtaining internationally agreed upon limits since the conditions of broadcasting and telecommunications can vary so much from

one country to another. A comparison of standards is shown in the figure below. The limits are referred to a quasi-peak measurement on a 100 kc bandwidth set with the antenna 33 feet from the vehicle.

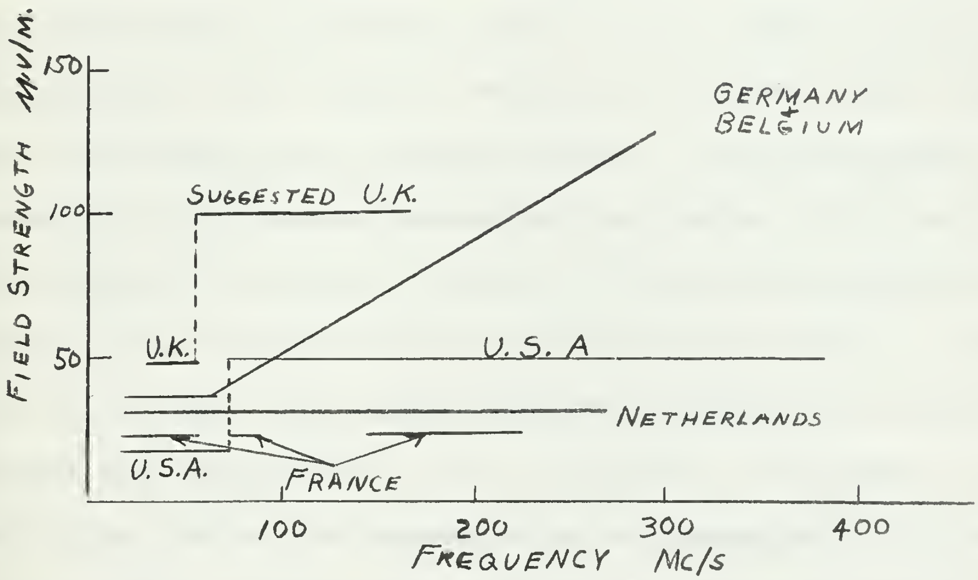

Fig. III - 2 Comparison of Field Strength Limits

In further support of an international standard for measuring ignition interference and limits, Egidi and Nano describe in ref. (49) a series of measurements of VHF radio interference caused by motorcycles and motor cars. In the case of the motorcycles, they found that completely shielded spark plugs, cables and coil was the best suppression arrangement. This resulted in the interference level being decreased to the ambient level. The next best suppression arrangement embodied the resistors in the spark plugs. This caused an interference reduction of between 19 and 33 db over the frequency range measured. Distributed resistance

and lumped resistors between the ignition coil and spark plug were only effective at the lowest frequency (54 mc). In the case of vehicles, the use of cables with distributed parameters and normal plugs gave almost as much interference reduction as the system having plugs with embodied resistors and distributed parameter cables. As a result of these measurements, the authors drafted an international standard for measurement with proposed limits. In conjunction with determining microwave communication system siting criteria, Scheldknecht describes in ref. (35) some quantitative measurements of the spectral density of radiated power in the vicinity of 900 mc. The median radiated power of the ignition pulses was determined to be -12 dbm and -22 dbm/mc of bandwidth for trucks and passenger cars respectively. The tests also revealed no definite reduction in radiated pulse power for conventional suppression techniques. It was theorized that at UHF the spark plug shank is an appreciable portion of a wavelength by itself and does not require low resistance connecting leads for efficient radiation.

CHAPTER III
BIBLIOGRAPHY AND ABSTRACTS

1. Abatement of Radio Interference Caused by Motor Vehicles and Internal Combustion Engines, British Standard Code of Practice, British Standards Institution, London, England, 1947, CP 1001.

2. Aircraft and Vehicular Engine Radio Interference Limits: Dept. of Commerce 95316, Office of Technical Services.

3. D. W. Randolph, Aircraft -- Engine Radio Shielding, SAE JOURNAL, Vol. 50, pp. 538-541, Dec. 1942.

   "This paper outlines the important electrical requirements of radio ignition shielding. The reason for low resistance grounding and bonding of the shield is explained. A method for testing the resistance of plastic insulators to flashover is suggested, and a method developed in England for reducing spark plug electrode erosion is described."

4. L. C. Wolcott, Airplane Motor Radio Shielding, AVIATION ENGINEERING, Vol. 4, pg. 33, June 1931.

   "Discussion of new type of oil-proof shielded ignition cable produced by Pakard Electric Company. Gives technique for attaching connector to cable."

5. Airplane Radio Freed from Ignition Interference: SCIENCE NEWS LETTER, Vol. 23, pg. 40, 1933.

6. Allison -- Modification of Ignition Systems to Eliminate Radio Noise -- V-1710-93 Engines, U. S. Army Air Forces, Technical Order 02-5AD-16, January 1945, (PB 41355).

7. P. J. Kent, Automotive Industry's Participation in Reduction of Radio and Television Interference, SAE JOURNAL, Vol. 57, pp. 17-19, March 1949.

   Describes the methods prescribed by the SAE Vehicle Radio Interference Committee for suppressing ignition radiation.

8. B. H. Short, Automotive Radio Noise Elimination, QST, Vol. 27, pg. 17, April 1952.

   "This article discusses the basic causes of generated noise and describes methods, developed over a long period of time in the automotive laboratories, that are based on sound engineering principles and that have been proved to work."

9. V. Welge. Balanced Two-wire Method to Reduce Ignition Interference, COMMUNICATIONS, Vol. 29, pp. 22-24, May 1949.

10. The Capacity Spark Discharge of Ignition Systems, British Electrical and Allied Industries Research Association, M/T 75, 1944.

11. W. Nethercot, Car Ignition Interference, WIRELESS ENGINEER, Vol. 26, No. 311, pp. 251-255, Aug. 1949.

Advances an alternate theory for the wideband radiation from the ignition current based on travelling waves in the ignition wires. Describes tests of the effectiveness of resistors at the distributor and spark plug ends.

12. C. C. Eaglesfield, Car Ignition Radiation, WIRELESS ENGINEER, Vol. 28, pp. 17-22, Jan. 1951.

"This paper extends the theory previously given by the writer to cover resonances in the ignition system and the addition of resistors for suppression. It is shown that, in practice, resonances do not appear to play an important part for the band of frequencies 40 - 650 Mc/S. The formulae for suppression ratio are checked against published measurements."

13. Check Motor Vehicle Interference with Radio Reception, SAE JOURNAL, Vol. 55, pp. 93-94, March 1947.

14. J. D. Noyes, Commercial Mobile Radio Interference Shielding, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, pg. 258, Oct. 1960, (AD-253 015).

"This paper discusses the present day automobile from the standpoint of radiated e-m interference. The various interference sources located in the automobile and the characteristics of each type of interference generated are considered. The effects of these interference signals on radio receivers are presented. Practical approaches to the reduction and control of automotive and, in general, gasoline engine generated interference are considered. A suppression kit, economically feasible for commercial use, is treated in detail."

15. A. M. Intrator, Comparison of Army and Navy Specifications with Particular Regard to Ignition Interference, NCEL, March 29, 1951, N-019, (PB 154 637).

16. Development of Universal 12 and Dual 6 Cylinder Integrally Shielded Distributors, Electrical & Mechanical Design Corp., August 1951, (ATI 170 165, (3-4)).

"The purpose was to design and develop an engineering model of a universal 12 and dual six-cylinder integrally shielded distributor which would eliminate radio interference emanation. Data are presented on various components. It is concluded that if the distributors are properly installed and assembled according to recommendations and precautions listed, they should eliminate all unwanted radio interference."

17. Distributed Resistance Ignition Cable, ELECTRONICS, Vol. 24, pg. 204, July 1951.

Describes suppressor ignition cable having a distributed resistance of approximately 5000 ohms per foot which minimized ignition interference at TV and FM frequencies.

18. Disturbing Effects of Electric Ignition Systems of the Motors on Wireless Reception in Aircraft, ELEKTROTECHNISCHE ZEITSCHRIFT, Berlin, Vol. 44, pg. 537, 1923.

19. F. J. M. Lauer, J. W. Allnatt, J. J. Randal, Effects of Mistuning the Receiver on the Reception of AM and FM VHF Broadcasting, Case No. 3355, Post Office Engineering Department, London, England, Radio Report #2124, Sept. 18, 1951, (ATI 160 578, (3-1)).

"The effect of VHF broadcast receiver mis-tune is more serious for FM than for AM reception in respect of receiver noise, ignition-system interference and quality of reproduction."

20. Peters, Blackburn & Hannon, Electrical Character of Spark Discharge of Automotive Ignition Systems, JOURNAL OF RESEARCH OF THE NATIONAL BUREAU OF STANDARDS, Vol. 19, pg. 401, Oct. 1937.

"To determine the character of a spark discharge it is necessary to determine current and voltage as functions of time. The measurement of these quantities is facilitated by the use of the cathode ray oscillograph, but due consideration must be given to the effect of the measuring circuit,

including connections to the oscillograph, on the character of the discharge, especially in investigations of automotive ignition circuits.

"Two methods suitable for measuring the current in the discharge with the cathode ray oscillograph are (1) measurement of the voltage across a known inductance, and (2) deflection of the cathode beam by the magnetic field set up by the current. The paper deals in detail with the application of these two methods, including, in the first method, the equations by which the current is derived, and the method of calibrating the measuring circuit in both methods.

"Analysis is made of oscillograms obtained by both methods for the discharge in the calibrating circuits and in a typical ignition circuit. Crest currents 50 to 80 amp were measured. The frequencies ranged from 6 to 10 Mc/s, the decrements from 0.08 to 0.40, and the energy expended from 0.0023 to 0.0135 j. The expended energy is found to agree with the energy known to be stored in the capacitance of the circuit at the beginning of the discharge."

21. L. F. Curtis, Electrical Interference in Motor Car Receivers, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 20, pp. 674-688, April 1932.

"In the high tension and low tension ignition circuits of present day motor cars there are three sources of high frequency transients in time and space. In the lighting generator there is another. These radiations and their reduction to acceptable levels to avoid pick-up by the supply and antenna leads to the receiver and the best form of antenna are discussed."

22. R. Sappe, Eliminating Noise in Auto Radios, RADIO AND TELEVISION NEWS, Vol. 56, pp. 50-51, Aug. 1956.

Identifies source of vehicular radio interference and describes methods of eliminating it.

23. Eliminating Spark Plug Disturbance in Automobile Radio, RADIO ENGINEERING, Vol. 13, pg. 20, 1933.

24. Elimination of Radio Interference in Aircraft, U. S. Bureau of Aeronautics, NAVAER Report 16-5Q-517, March 1946, (PB L 81895).

25. Gifford, End Auto Radio Interference, RADIO-ELECTRONICS, Vol. 33, pp. 40-41, January 1962.

26. H. Diamond and F. G. Gardner, Engine-Ignition Shielding for Radio Reception in Aircraft, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 18, pg. 840, May 1930.

"The use of highly sensitive receiving equipment on aircraft has made the problem of airplane-engine ignition shielding an important one. Ignition shielding consists of so confining the electrical fields of the ignition system that no interfering signal can be set up in the radio receiving circuits. The problem in ignition shielding is chiefly the electrical and mechanical design of the arrangement for shielding, as it is much more difficult to secure an assembly which will not adversely affect the engine ignition system than to obtain complete freedom from interference for the radio equipment.

"The Bureau (of Aeronautics) has been in active cooperation with airplane engine, magneto, spark plug and cable manufacturers in an effort to develop a safe method for effecting this shielding and to make the necessary equipment commercially available. A metallic ignition manifold is employed with high tension cable drawn through it in the usual way The leads from the manifold to the spark plugs and the groups of leads from the manifold to the magneto outlets are enclosed in liquid-proof flexible aluminum tubing with copper braid on the outside to insure effective shielding. Each flexible tubing is suitably fitted to the ignition manifold and to the magnetos or spark plugs, as the case may be. The magnetos are provided with covers which completely enclose the distributor blocks. A single outlet permits the use of an elbow fitting for connection to the large flexible metal tubing. This elbow fitting differs for different types of engines. Outlets are provided in the elbows for the booster and ground leads. The spark plugs are of a type in which the shield is an integral part and are provided with elbows for connection to the smaller flexible metal tubing. The ignition switch is enclosed in a metal cover, the booster magneto is also covered, and the leads from the magnetos to the ignition switch and booster magneto are enclosed in flexible metal tubing. The complete assembly insures electrical safety; mechanical sturdiness; liquid-proofing of magnetos, spark plugs and ignition cable; and ease of installation and of servicing."

27. Campbell, Exit Ignition Noise, QST, Vol. 43, pp. 30-33, May 1959.

28. H. Page, G. G. Gouriet, An Experimental Investigation of Motorvehicle Ignition Interference, B. B. C. QUARTERLY, Vol. 3, pp. 182-192, October 1948.

Discusses the effects of ignition interference on FM reception at frequencies of 45 and 90 Mc. Concludes that interference was less with horizontal polarization, and at 90 Mc (6 to 10 db)."

29. R. W. George, Field Strength of Motorcar Ignition Between 40 and 450 Mc, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 28, pp. 409-412, September 1940.

"Measurements of motorcar-ignition peak field strength were made on frequencies of 40, 60, 100, 140, 180, 240, and 450 megacycles. Propagation was over Long Island ground and the receiving antennas were 35 feet high and 100 feet from the road. Under these conditions, the average field strength varied about 2 to 1 over the frequency range. Curves show the maximum field strength versus frequency for 90, 50, and 10 per cent of all the measurements. Vertical and horizontal polarization are compared showing slightly greater field strength, in general, for vertical polarization. New cars, old cars, and trucks are compared showing no large differences of ignition field strength.

"Some of the factors involved in motorcar-ignition radiation are mentioned. Theoretical propagation curves are included and the measuring system is briefly discussed."

30. M. C. Anderson, How to Eliminate Auto Radio Static, RADIO AND TELEVISION NEWS, Vol. 41, pp. 38-39 +, May 1949.

Describes methods for checking for ignition radiation sources in an automobile and methods of correcting them.

31. L. F. Curtis, Ignition Disturbances, Proceedings of the Radio Club of America, Oct. 1936.

32. G. F. Newell, Ignition Interference at Frequencies Below 100 Mc/s: The Mechanism of Its Production, B. B. C. QUARTERLY, Vol. 9, No. 3, pp. 175-184, March 1954.

33. W. Nethercot, Ignition Interference; Its Nature, Magnitude, and Measurement; Methods of Suppression, WIRELESS WORLD, Vol. 53, pp. 352-357, Oct. 1947; Vol. 53, pp. 463-466, Dec. 1947.

34. John B. Ledbetter, Ignition Interference to FM and Television, RADIO-ELECTRONICS, vol. 20, pp. 30-31, June 1949.

Describes a series of tests by the RMA-SAE Committee on Vehicle Radio Interference to determine the tolerable limits of interference. Tests indicated that interference could be kept within tolerable limits through the use of suppressors.

35. R. Scheldknecht, Ignition Interference to UHF Communication Systems, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. RFI-4, No. 3, pp. 63-66, Oct. 1962.

"Some quantitative measurements on vehicular ignition noise are reported in terms of the spectral density of radiated power in the vicinity of 900 Mc, to assist in predicting the amount of interference which must be considered in siting microwave communication systems.

"The median radiated power of the ignition pulses was determined to be -12 dbm and -22 dbm/Mc bandwidth for trucks and passenger cars respectively. Conventional suppression techniques, normally effective at lower frequencies, were found to have no effect. Polarization of the receiving antenna also had no statistical effect.

"The effects of such interference on the FM receivers and multiplex equipment of a troposcatter communication link were also evaluated. The pulses were audible whenever their received level exceeded the desired signal level."

36. A. H. Ball, W. Nethercot, Ignition Interference with Television Reception, INSTITUTION OF MECHANICAL ENGINEERS, LONDON, PROCEEDINGS (AUTOMOBILE DIVISION), Vol. 100, pt. 1, Sept. 1953: INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, PROCEEDINGS, pg. 299, Sept. 1953.

The paper deals with the measurement of the interference and methods of suppression and shows how the interference producing radiation arises from the capacitance component of the high-voltage ignition spark. A large number of measurements of the interference producing radiation from vehicles, both with and without suppression, were made and curves showing the magnitude of the interference and the suppression efficiency of resistors are given.

37. C. M. Dean, Ignition Noise on the VHF and UHF, QST, Vol. XXVIII, No. 1, pg. 44, Jan. 1944.

"The use of much higher frequencies in mobile communication has increased the problem of electrical noise elimination. The author reviews the causes of increased ignition interference and indicates some factors which must be taken into consideration if satisfactory noise reduction is to be obtained."

38. G. Etzel, W. Pharo, Installation of Interference-Reduction Kit on Six Cylinder and Dual Six Ignition Engines, Air Material Command, Watson Lab., Army Signal Corps, March 1950, (ATI 73860, (3-4)).

"The installation is made for the purpose of controlling electrical disturbances that cause undesirable responses or malfunction of electronic equipment. The installed mechanical and electrical interference-reduction components of the kit include coil, distributor, spark-plugs, high-tension cables, generator, current-voltage regulator, associated filters, and low-tension wiring. The installation and shielding procedures described are directly applicable to all vehicles using engines listed in the appendix."

39. Elbert Robberson, Interference Problems on Small Boats, RADIO AND TV NEWS, Vol. 57, pp. 38-39, May 1957; U. S. BUREAU OF SHIPS JOURNAL, Vol. 7, No. 3, pg. 29, July 1958.

Describes methods of shielding ignition interference sources in lieu of resistor spark plugs which affect engine performance. Other sources are also identified with recommended cures.

40. A. Mason Brown, Interference Suppression for Automotive Ignition Systems, Naval Civil Engineering Lab., Port Hueneme, Calif., Proj. NY 411 002-7, Technical Report No. 070, Feb. 18, 1960.

"A low-cost radio interference suppression harness for automotive ignition systems is being developed and is based on the following premises: (1) that mild steel sheet-metal stampings could be substituted for bronze castings as suppression shields; and (2) that standardized parts might be designed to fit all engines. Fabrication of the shielding components from sheet metal successfully resulted in providing satisfactory suppression characteristics. Standardization of parts to include 3 different

types of engines was partially successful. Prototype harnesses performed their function satisfactorily under in-service tests on Navy vehicles. Radio interference suppression was good, ignition system operation was good, and equipment maintenance was nominal. No operating failures from moisture condensation were experienced. However, difficulties were experienced in making the original installations, and inconveniences were encountered by mechanics in dismantling and reassembling the harness components while making engine repairs."

41. Interference with Radio Reception on Aeroplanes, ELETTROTECNIA, Vol. 19, pg. 724, 1932.

42. Is the Interference with Reception in Aircraft Due Entirely to the Ignition System?, L'ONDE ELECTRIQUE, Vol. 9, pg. 446, 1930.

43. Jet Ignition Systems, AERO DIGEST, Vol. 64, No. 2, pg. 28, Feb. 1952.

44. E. V. Kavanaugh, Investigation of the Effect of Resistor-Suppressors upon Cold Starting (Truck $\frac{1}{4}$ ton 4 x 4), Coles Signal Lab., Signal Corps, U. S. Army, March 24, 1949.

45. Killing Auto QRM in Your Receiver, RADIO NEWS, Vol. 19, pg. 521, March 1938.

46. W. B. Smith, Magneto-Ignition Oscillations and Their Elimination, CANADIAN JOURNAL OF RESEARCH, Vol. 12, pp. 505-518, April 1935.

47. A. H. Ball, W. Nethercot, The Magnitude of the Radio Interference in the Television Band from Ignition Systems of Motor Vehicles, British Electrical and Allied Industries Research Association, Rept. M/T 123, 1951.

48. W. Hartell, V. Podbielski, Measurement and Analysis of Ignition Interference -- 150 KC to 10 KMC, Master's Thesis, U. S. Naval Postgraduate School, May 1962.

"Results are given for screen room measurements of a mock-up ignition system over the frequency range of 150 KC to 10 KMC. Resistive high-tension leads are compared with regular low resistance ignition leads. Measurements were also made on a 1962 model car over the same frequency range and are compared with a proposed international limit for ignition interference. Waveforms of current flow through one spark plug and spectrum analyzer displays of radiation are shown and discussed."

49. E. Nano, C. Egidi, Measurement and Suppression of VHF Radio Interference Caused by Motorcycles and Motor Cars, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. 3, No. 1, May 1961.

"The problem of ignition interference and its reduction has been emphasized in Europe, due to the simultaneous growth in both number of motor vehicles, and in the number of FM and TV receivers. The paper reports the results of a large number of interference measurements made on automobiles and motorcycles. The data include the effects of various suppression schemes. As a result of these measurements, and taking into account existing European standards, a draft of an international standard was prepared for submittal to CISPR. This proposed standard covers both methods of measurement and limits."

50. C. C. Eaglesfield, Motor Car Ignition Interference, WIRELESS ENGINEER, Pg. 265, Oct. 1946.

"A simple theory is given of the mechanism of motor car ignition interference. Each spark gives a radiated field of the form of an impulse of easily estimated area and extremely short duration. A car gives a train of such impulses for each normal spark. The theory seems to fit the known facts."

51. F. R. W. Strafford, Motor Car Interference, WIRELESS WORLD, Vol. 44, No. 5, pp. 103-104, Feb. 2, 1939; No. 6, pp. 130-132, Feb. 9, 1939.

52. Motor Vehicle Ignition Interference, Post Office Memorandum, WP2/3, No. 707, (British).

53. H. B. Davis, Noise Suppression on Small Boats, RADIO NEWS, Vol. 32, pp. 47-49, Oct. 1944.

54. Oscillations in the Magneto Ignition System and Their Elimination: CANADIAN JOURNAL OF RESEARCH, Vol. 12, April 1935.

55. R. Ruedy, Oscillations in Spark from Induction or Ignition Coils and Their Suppression, CANADIAN JOURNAL OF RESEARCH, Vol. 13, Sec. A, pp. 45-59, Sept. 1935.

56. B. H. Short, Physics of Automotive Radio Interference Elimination, GENERAL MOTORS ENGINEERING JOURNAL, Vol. 1, No. 5, pp. 36-40, March-April 1954.

Deals with three sources of radio interference in

the ignition system, i.e., ignition condenser and breaker points, rotor gap, and spark plug. Suppression by filtering and shielding are described. Suppression of interference from the generator circuits are also dealt with.

57. Van Syckel, Production of Ignition Radio Shields, IRON AGE, Vol. 158, pp. 56-58, Aug. 29, 1946.

Production of ignition radio shields for aircraft, involving the extensive use of silver alloy brazing and special jigs, fixtures and gages, is described. The production procedures outlined are also applicable to similar units for automobile and marine shielding.

58. Fernald, Quiet Please -- Suppression of Electrical Interference in Vehicles, RADIO NEWS, Vol. 30, pp. 41-42, July 1943.

59. L. H. Daniel, The Radiated Short Wave Disturbance from Automobile Ignition Systems, British Electrical and Allied Industries Research Association, Rept. M/T 63, 1939.

60. L. H. Daniel, The Radiation from Automobile Ignition Systems at Ultra High Frequencies, British Electrical and Allied Industries Research Association, Report M/T 82, 1945.

61. B. G. Pressey, G. E. Ashwell, Radiation from Car Ignition Systems, WIRELESS ENGINEER, Vol. 26, pg. 31, Jan. 1949.

"This paper describes measurements which have been made of the field strength of the radiation from a typical motor-car ignition system, a matter of importance in connection with interference to television and other radio services. A wide-band (2.5 Mc/s bandwidth) measuring set with a cathode-ray indicator unit was used and the field strength recorded was that corresponding to the peak of the output signal. The results showed that the general level of the field was maintained throughout the frequency range and that its value was approximately 10 mV/m at a distance of about 30 ft. (9.14 metres). Measurements of the suppression of the radiation by the insertion of block resistors and resistive leads were also made. The secondary pulses, which are associated with each nominal spark, were also examined under unsuppressed and suppressed conditions. The second part of the paper describes measurements of the radiation from a basic

system consisting of a single plug and loop of wire. The resonances which occur in the lead when block resistors are inserted were also investigated and it was shown that for certain positions of the resistor there was an increase in the observed field strength."

62. RFI Generated by Motor Vehicles, Bureau of Ships, NAV SHIPS 900179, Jan. 1953, (AD 9038).

63. L. W. Thomas, Radio Interference Aboard Motor Torpedo Boats, BUSHIPS, March 1945, (PB 85950).

64. Radio Interference: Condensors for Suppression on Short Wave Lengths, ELECTRONICS, Vol. 116, pg. 378, March 20, 1936.

65. W. Nethercot, Radio Interference from Automobiles in the Range 30 - 220 Mc/S, British Electrical and Allied Industries Research Association, Rept. M/T 81, 1945.

66. A. H. Ball, W. Nethercot, Radio Interference from Ignition Systems -- Comparison of American, German, and British Measuring Equipment Techniques and Limits, INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, PROCEEDINGS, Vol. 108, pt. B, pp. 273-278, May 1961.

"The paper records the results of some tests made in the United States to compare results obtained with American, German, and British radio-interference measuring sets when measuring the interference radiated by the ignition systems of motor vehicles. The tests show the close agreement between the results obtained when using the various national measuring sets and confirm the reliability and consistency of measuring equipment conforming to the specification of the International Committee on Radio Interference (C.I.S.P.R.). They also attempt to establish a relationship between the results of peak and quasi-peak measurements. The paper also tabulates and discusses the test conditions specified in the various countries and quotes the limits of ignition interference recommended or statutory in the countries concerned. A direct comparison of these limits, which is made possible by these measurements suggests that the existing and proposed requirements of other countries are more onerous than those of the United Kingdom."

67. Radio Interference from Motor Vehicles -- Comparison of British and German Measuring Equipment, British Electrical and Allied Industries Research Association, 1953, Rpt. M/T 123.

68. R. Thurston, V. Messina, Radio Interference Investigation of the Electrical System of a Vehicle, National Co., Inc., 1957, (AD 108678).

69. Radio Interference Investigation Relative to Picket Boats; Letter Report, Navy Electronics Lab., Rept. No. 78, Sept. 1, 1948.

70. C. D. Humphery, Radio Interference Measurements on Pratt and Whitney Engines, Pratt and Whitney Aircraft Report 586, Dec. 1945.

71. E. Birch, Radio Interference Minimization Design on a Champion Spark Plug, Burroughs Corporation, Oct. 1953, (AD 35287).

"The Champion Spark Plug Company Model B 600 ERS Service Unit Spark Tester employs an electrical circuit which simulates an auto ignition system. Included in the electrical circuit of the unit are an on-off switch and a vibrating contact. There is also high voltage arising in the spark plug under test. These three sources of interference render this unit an excellent device for conducting research on minimizing interference from contact and high voltage arcing."

72. Leonard W. Thomas, Radio Interference on a Modern Parkway, U. S. BUREAU OF SHIPS JOURNAL, Vol. 4, No. 6, pp. 29-31, October 1955.

Ignition interference measurements in the frequency range 14 KC to 1000 MC were made adjacent to an expressway. Distances varied from 400 to 2700 feet. Highest levels of interference were from trucks powered by gasoline engines. None of the diesel powered trucks caused any noticeable interference. Tests were run continuously over a 40-hour period.

73. Radio Interference Radiation Tests on an Alternating Current Power System for Automotive Equipment, Naval Civil Engineering Lab., Port Hueneme, Calif., N-071, Jan. 1952.

74. N. Hendry, Radio Interference -- The Effect of Suppressors on Engine Performance, AUTOMOBILE ENGINEERING, Vol. 30, pp. 167-173, June 1940.

75. A. E. Teachman, Radio Noise in Aircraft Engines, AERONAUTICAL ENGINEERING REVIEW, Vol. 4, No. 8, Aug. 1945.

"Characteristics of the ignition impulse and its radio-frequency effects are outlined. It is shown

that resonant oscillations in the ignition system occur above 10 Mc and that resistance wire ignition cable markedly reduces the intensity of these oscillations. Filters for magneto grounding circuits are found to have a limited value in the VHF range. Shielding concepts and the principles of shielding design are presented with emphasis on the problem of obtaining continuity of the shield at joints and parting surfaces. Conducting gaskets of various types are described and the conditions that they must satisfy to achieve shielding effectiveness are stated. Some recent tests show wide differences in the shielding effectiveness of various types of flexible shielding conduit. Practical testing methods for the design engineer are suggested."

76. Neubauer, Radio Reception Interferences by the Ignition System. Partial Report I: Evaluation of Various Spark Plug Shieldings in Ultra Short-wave Reception, AAF T-2 Translation 909, Nov. 1946.

77. Radio Shielding of Aircraft Engine Ingition Systems, Army Air Force Material Command, Serial TN-92-1, pp. Xi-Xii, May 1944.

78. Radio Shielding of Aircraft Ignition Systems, Air Material Command Engineering Division, Aircraft Lab., Wright-Patterson AFB, July 1946, (PB-117 751).

79. V. Zeluff, Reduced Ignition Interference, ELECTRONICS, Vol. 22, pg. 118, July 1949.

Describes tests by the Electric Auto-Lite Company with resistor type spark plugs.

80. L. G. Sands, Reducing Citizens Band Ignition Noise, ELECTRONICS WORLD, Vol. 66, pp. 36-38, Aug. 1961.

81. W. Nethercot, Relation Between the Sparking Plug Current and the Short Wave Radiation Produced by Ignition Systems, British Electrical and Allied Industries Research Association, Rpt. M/T 53, 1938.

82. M. S. Kay, Servicing Hints on Auto Radio Interference, RADIO NEWS, Vol. 33, pp. 48-49, April 1945.

83. W. Nethercot, Short-Wave Interference from Ignition Systems, British Electrical and Allied Industries Research Association, Rpt. M/T 47, 1937.

84. Short-Wave Interference from Ignition Systems, British Electrical and Allied Industries Research Association, Rpt. M/T 62 and Rpt. M/T 63, 1938.

85. F. J. M. Lauer, J. W. Allnatt, J. J. Randall, The Signal/Interference Ratios Needed for the Satisfactory Reception of AM and FM UHF Broadcasting in the Presence of Ignition-System Interference, Case No. 3355, Post Office Engineering Department, London, Sept. 18, 1951, (ATI 164 573 (3-1)).

"A series of subjective tests is described which was designed to determine the signal/interference ratios needed for the satisfactory reception of UHF broadcasting in the presence of motor-vehicle ignition system interference. The results are quoted for the reception of AM and ± 75 Kc FM signals using an effective audio bandwidth of 10 Kc. The tests show that for equal disturbances the tolerable r-f level of ignition-system noise may be about 15 db higher for FM than for AM reception, for interference just strong enough to cause annoyance."

86. Spark Plug Reduces Interference, RADIO CRAFT, Vol. 19, pg. 86, Sept. 1948.

Describes a resistor spark plug developed by the Electric Auto-Lite Co. that suppressed radiation to 35 millivolts/m from 540 Kc to 150 Mc at 50 feet from engine.

87. Spark Screening of Aircraft Engines, ELEKTROTECHNISCHE ZEITSCHRIFT, Berlin, Vol. 51, pg. 1610, 1930.

88. W. Nethercot, The Study of the Capacitance Spark in Automobile Ignition Systems with Special Reference to Short Wave Radio Interference, British Electrical and Allied Industries Research Association, Rpt. M/T 62, 1939.

89. Browning, Suppressing Auto Radio Noise, RADIO NEWS, Vol. 15, pg. 410, Jan. 1934.

90. E. A. Robertson, L. M. Hull, Suppressing Ignition Interference on Radio Equipment of Aircraft, SAE JOURNAL, Vol. 27, pg. 28, July 1930.

"After discussing the nature of the interference, the authors discourse on the suppression of ignition interference by means of shielding. A constructive tendency in recent shielding development, they say, is the extension of the idea that a shielding system which holds together under service

conditions, if intelligently designed, may be just as successful in keeping water, oil, and dirt out of the ignition as it is in keeping noise out of the radio. The remainder of the paper is devoted to a discussion and illustrations of various shielding systems now in commercial or experimental use, which are designed for complete housing of all important current-carrying circuits on the airplane engine. In the discussion, the belief is stated that no shielding at present has fully met the day-in-and-day-out grind of transport operations, and that it probably will develop for some time yet and will be evolved slowly. Tests of radio equipment made in a four-place cabin plane, having a J-5 nine-cylinder engine that was not shielded, are described. Doubt is expressed whether a worthwhile distinction will be made between the necessary shielding for long-wave and short-wave reception in the plane. The remainder of the discussion is largely concerned with details regarding the merits of vertical versus horizontal antennas, sensitivity of receiving sets, the best types of mast and their manner of mounting, and the like."

91. Suppressing Radiation from Car Electrical Systems, WIRELESS WORLD, pg. 18, July 14, 1933.

92. F. E. Butler, Suppressing Radio Noise in the Jeep, ELECTRONICS, Vol. 16, pp. 96-99, Dec. 1943.

Discusses minimizing interference in communication jeeps by careful body bonding and standardized filtering.

93. C. Attwood, Suppression and Car Performance, WIRELESS WORLD, Vol. 44, No. 15, pp. 345-46, April 15, 1939.

94. C. Attwood, B. Cole, Suppression and the Petrol Engine, WIRELESS WORLD, Vol. 46, pp. 288-290, June 1940.

95. G. Browning, R. Hoskins, Suppression of Auto Radio Noise, ELECTRONICS. Vol. 6, pg. 273, Oct. 1933.

Results of tests relating radiated interference to distance for a given frequency. Recommendations for the locating of the radio antenna and installation of the radio are given.

96. Suppression of Ignition Systems of Automobiles, British Electrical and Allied Industries Research Association, Rpt. M/T 28, 1934.

97. Test and Evaluation of Distributed Resistance Ignition Cable, Naval Air Test Center, Patuxent River, Maryland, Aug. 1954, (AD-39872).

"Investigations of the effectiveness of distributed resistance ignition cable as compared to lumped suppressors in the control of impulse interference from vehicular ignition systems were performed. The results of these investigations indicate a marked similarity in the interference suppression characteristics of the two methods. Supplementary tests showed that the effectiveness of the distributed resistance cable can be greatly improved by the addition of shielding at each spark plug."

98. Test of Braid Shielded Ignition Cables for Tactical Vehicles, Coles Signal Lab., Test Report # T-1279, Aug. 1, 1952.

"Both the Auto-Lite single braid shield and the General Electric double braid shield ignition cables provide adequate shielding to meet the requirements of MIL-S-10379-A when installed in typical tactical vehicles in conjunction with integrally suppressed spark plugs and ignition units."

99. Guy D. Johnson, Jr., Tests on Integrally Shielded and Suppressed Champion Type RC-10S No. 1283 and AC type 435 BA Automotive Spark Plugs, Detroit Signal Lab. Engineering Memo D-186-E-S-45, Nov. 1944.

100. W. Scholz, G. Faust, The Ultra Short Wave Interference Suppression of the Electrical Ignition System of Motor Vehicles, TELEGRAPHEN-UND RADIOGENOOTSCHAP, Vol. 28, No. 11, pp. 409-411, Nov. 1939.

101. L. T. Scharmen, Use of Conductive Rubber for Vehicular Radio Interference, U. S. Detroit Signal Lab. Engineering Memo, #D-259-E-S-45, Feb. 1945, (PB L 85962).

102. Anderson, Vehicular RFI Conference, QST, Vol. 43, pg. 39, Oct. 1959.

103. Vehicular Radio Noise Suppression, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, pp. 12-19, Dec. 1954, (AD-76 686).

"This paper deals with the sources of interference present in the ignition and charging circuits,

and describes methods of suppressing these noises. Gage noises and their suppression are covered. Various additional suppression procedures are described. In order to consider the most effective suppression for the various devices in a vehicular electrical system, it is necessary that we understand the characteristics of these components. For that reason we shall break the complete electrical circuit into two functional groups."

104. Gilbert Sunbergh, VHF Ignition Noise, ELECTRONIC INDUSTRIES, pp. 94-97, Nov. 1944.

"Study of the aircraft radio noise problem yields new facts of vital interest to all radio manufacturers."

105. R. L. Baker, J. LeFort, VHF-UHF Ignition Interference Survey, Naval Air Test Center, Patuxent River, Maryland, Jan. 1952.

"Tests with the AN/ARC-27 communication equipment and AN/ARR-27 radar relay receiver indicated that present ignition systems for aircraft reciprocating engines are satisfactory and will not cause significant interference in the VHF-UHF range with proper production and maintenance."

CHAPTER IV

INTERFERENCE FROM FLUORESCENT LAMPS

A fluorescent lamp contains low pressure mercury vapor. When a voltage is applied to the electrodes of the tube the mercury vapor is ionized by the flow of electrons in the tube. The mercury vapor is then de-ionized and releases ultra-violet radiation. In order to radiate light in the visible region the inside of the tube is phosphor coated. The coating is excited by the ultra-violet radiation and re-radiates visible light. Since, in effect, the lamp operates with a continuous arc, it causes radio interference. It has been determined that there are three ways that the interference can be transmitted to a receiver:

(1) Direct radiation from the lamp to the receiver's antenna;

(2) Conduction along the power line from the lamp to the receiver;

(3) Radiation from the power line with pick up by the receiver's antenna.

One of the earliest published measurements of radiation from a fluorescent lamp, ref. (20), was conducted by C. Young, in 1944. Direct radiation at 1000 kc from a filtered and unfiltered 15-watt lamp is shown in the table (Fig. IV - 1).

The results indicate that interference drops off rapidly with distance and that capacitor type filtering is very

Distance in Feet between Antenna and Lamp	Radio Noise Microvolts/meter Unfiltered	Radio Noise Microvolts/meter Filtered
1	2000	85
2	800	30
3	400	14
4	200	--
5	100	--
6	40	--
7	20	--

Fig. IV - 1 Table of Values of Radiation from a 15-watt Fluorescent Lamp

effective. Measurements of conducted interference along the supply lines at 1000 kc were as follows:

Unfiltered -- 390 microvolts

Filtered -- 19 microvolts

It was concluded that direct radiation at the frequencies measured was not a problem, but that radiation from and conduction along supply lines are important factors. Certain fluorescent tubes gave off considerably more interference than others due to oscillations in the tube. A noticeably bright spot near one of the heaters would appear in the oscillating tube. Meaurements taken several years later, reported in ref. (9), indicated that the interference occurred at intervals over a wide band of frequencies, extending from less than 100 kc to 3000 mc, and that there was no harmonic relationship between the observed frequencies. Measurements of the interference levels of filament (preheat) type versus the instant start (cold cathode) type fluorescent tubes were were conducted by the Charleston Naval Shipyard and described

in ref. (23). It was determined that the interference levels generated by the instant start lamps were considerably higher than those generated by the filament type lamps. This was true for both radiated and conducted interference levels.

Wright and Zimmermann proposed, in ref. (4), a method of evaluating the effectiveness of noise suppression schemes by measuring the line to ground voltages. Their proposal was to compare the ballast to be evaluated with a reference ballast. This is done by rapidly switching the lamps from reference to test ballasts and comparing the line to ground voltages of the two ballasts. Expressed mathematically the comparison ratio in db equals 20 $\log_{10} V_t/V_r$ where V_t is the average line to ground voltage of the test ballast and V_r is the average line to ground voltage of the reference ballast. The suggested filtering scheme for the reference is the application of 0.01 microfarad capacitors across each lamp in the system.

The Material Lab., New York Naval Shipyard, has conducted a series of tests on interference from both hot and cold cathode type lamps. The results are reported in refs. (5), (6) and (10). It was found that most of the radiated radio interference from various types of fluorescent lamps occurs at frequencies below 10 mc. The magnitude of the maximum peak interference, when measured three feet from the lamp, was in the order of thousands of microvolts. The maximum

interference usually occurs in the very low frequency range around 15 kc and falls off as the frequency increases. It was found that fitting the fixture with a louver of either conducting glass, 50 ohms per square foot, or an aluminum honeycomb reduced the radiation to zero with only a 15% reduction in light.

Investigations into the origin of interference in the lamp were carried on by van Boort, Klerk, and Kruithof and are described in ref. (19). By means of an oscillogram the following waveforms were determined with the lamp circuit ungrounded.

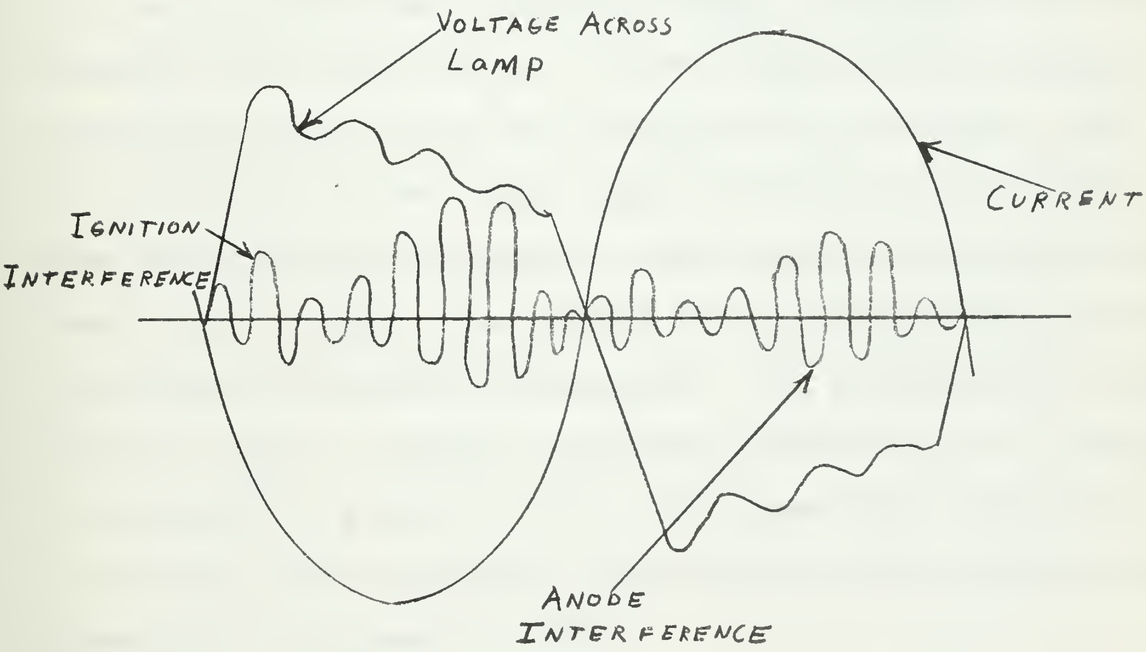

Fig. IV - 2 Fluorescent Lamp Waveform

It was shown that the high-frequency voltage is very strong at the beginning of each half-cycle, just when the voltage across the lamp reaches the ignition potential.

This was called the "ignition interference". In many cases a higher peak appears at the end of each half cycle. This was termed "the extinction interference". It was further determined that ignition and extinction oscillations are generated during the half cycle in which the electrode concerned is the cathode. This was therefore designated as cathode interference. The oscillations in the middle of the half cycle arise when the electrode concerned is the anode, and these are referred to as anode interference. Further investigation showed that the cathode interference is made up chiefly of components with frequencies higher than about 350 kc while the anode interference contained mainly components with frequencies lower than 250 kc. It was theorized that cathode interference was due to the oscillations of positive ions in the potential minimum which occurs in front of the cathode when the discharge current is lower than the saturation current of the cathode. As a means of suppressing conducted interference the authors recommended: (1) splitting the choke into two parts to reduce symmetrical components; (2) using a low capacitive choke to reduce the asymmetrical component; (3) using a three capacitor delta filter which reduces the symmetrical component by 35 db.

CHAPTER IV
BIBLIOGRAPHY AND ABSTRACTS

1. Avoiding Radio Interference from Fluorescent Lighting Installations, ELECTRONIC NEWS, Vol. 53, No. 9, Pg. 29, May 1944; RADIO NEWS. Vol. 32, pg. 149, Nov. 1944.

2. A. C. Hoyle, Cutting Interference from Fluorescents, ELECTRICAL WORLD, Vol. 115, pg. 1344, April 19, 1941.

   Describes three ways for interference to reach the radio receiver: (1) direct radiation from the lamp to aerial circuit; (2) direct radiation from electric supply line to aerial circuit; (3) line feedback from lamp through service line to radio. Methods of suppression are also discussed.

3. D. B. Clark, Evaluation of Interference Suppression of Fluorescent Lamps, TR 166, Naval Civil Engineering Lab., Port Hueneme, Calif., Oct. 6, 1961, (AD-265 780).

   "The evaluation of the interference characteristics of commercial fluorescent fixtures advertised as interference-free, including both hot-cathode and cold-cathode lamps, demonstrates that those fixtures which are completely enclosed electrically are free of interference. A hot-cathode instant-start fixture, with conducting-glass door panel, interchangeable with an aluminum honeycomb door panel covering a one-piece metal fixture proved to be greater than 6db below the specification limits shown in BuShips MIL-I-16910(A). The cold-cathode lamps tested failed to meet specification limits. An enclosed fixture which failed to pass specification tests was modified by electrically bonding at all junctures at approximately 2-inch intervals, including the 2-inch by 2-inch by 1-3/8-inch-deep grill. By this means interference was reduced to an acceptable level. Light emission from the interference-free commercial fixture was measured, and the conducting-glass panel and the honeycomb aluminum panel caused a loss of approximately 10%. Replacement of the nonconducting panel-closure gaskets with radio-frequency-suppressing gasket stripping, resulted in an average reduction of 7 db in the magnetic induction field."

4. F. H. Wright, S. A. Zimmermann, Evaluation of Radio Influence Voltages in Fluorescent Lighting Systems, ELECTRICAL ENGINEERING, Vol. 75, pp. 272-274, March 1956.

The principal subjects considered are:
(1) The mechanism of r-f energy coupling between the lighting system and the radio;
(2) A test method that makes possible the assignment of an approximate numerical value to the probable radio influence voltage of a fluorescent lighting system;
(3) A statistical means of critically evaluating the probable radio influence voltage of a fluorescent light system.

5. Gerald Roca, Evaluation of Radio Interference from Hot Cathode Fluorescent Lamps, Material Lab., New York Naval Shipyard, Brooklyn, July 31, 1957, (AD-143 626).

"The report shows a method of virtually eliminating radiated radio interference from hot cathode fluorescent lights by the use of suitable shielding materials in the fixture. These materials are conducting glass and metallic honeycomb louvers. These, together with the use of suitable line filters to reduce the conducted radio interference to within prescribed military specification limits, can eliminate fluorescent lights as a significant source of radio interference in military installations."

6. Fluorescent Lighting, Interference Free, Material Lab., New York Naval Shipyard, Brooklyn, Jan. 7, 1958, (AD-158 138).

"Various gaseous-discharge illuminating devices were tested for radio interference. Results indicated that most of the radiated radio interference from fluorescent lamps occurred at frequencies below 10 mc. In general, under equal conditions, the cold cathode type of fluorescent lamp did not appear to have significantly less radio interference than a hot cathode type lamp. The order of maximum peak interference from fluorescent lamps was in the thousands of microvolts; this maximum interference usually occurred in the very low frequency range around 0.015 mc and diminished as the frequency increased. No large amount of interference from fluorescent lighting aboard ship was encountered when antenna leads and receivers were adequately shielded. Interference was encountered from fluorescent lamps on shore installations. A technique was developed to reduce the radio interference by using rapid start lamps and installing a "pi" type power line filter in the fixture, together with the installation in the bottom of the

fixture of a louver of conducting glass (50 ohms per square) or a honeycomb louver of aluminum."

7. Fluorescent Lighting May Affect Radio Reception, SCIENCE NEWS LETTER, Vol. 50, pg. 207, Sept. 28, 1946.

8. L. Blok, H. F. Oscillations in Sodium Lamps, PHILIPS TECHNICAL REVIEW, Vol. 1, pp. 87-90, March 1936.

9. Interference from Fluorescent Tubes, WIRELESS WORLD, Vol. 56, No. 3, pp. 93-94, March 1950.

   Describes measurement and waveform of interference from fluorescent tubes that were oscillating near one of the heaters. Methods of suppression are also discussed.

10. Gerald Roca, Investigation of Radio Interference from Cold Cathode Fluorescent Lamps, Material Lab., New York Naval Shipyard, Brooklyn, July 11, 1957, (AD-140 888).

   "The radio interference was analyzed and measured from a production model of an 85-w cold cathode fluorescent lamp (SR-24-L4) manufactured by the Cold Cathode Lighting Corp., Long Island City, N. Y. which uses a metallic honeycomb louver (Honeylite). The louver holes are ¼ in. deep and 5/16 in. across the diagonal of the hexagon. Two 4-ft. CC-35-IS cold-cathode lamps were used. Although the measured radiated radio interference 3 ft. directly below the fixture was as much as 2600 μv/m (at 0.02 mc) with the louver open, such interference was zero throughout the 0.14- to 1000-mc range when the louver was closed. The conducted radio interference measurements were within the limits of Spec. MIL-I-16910A dated 30 Aug. 1954. Light transmission of the honeycomb was about 85% directly below the fixture."

11. J. W. Culp, Noise in Gaseous Discharge Lamps, ILLUMINATING ENGINEERING, Vol. 47, pp. 37-46, January 1952.

12. H. L. Steele, Jr., A Preliminary Report on Physical Processes in the Fluorescent Lamp which Cause Radio Noise, ILLUMINATING ENGINEERING, Vol. 49, No. 7, pp. 349-356, July 1954.

13. L F. Shorey, S. M. Gray, A Preliminary Study of Radio Interference as Caused by Fluorescent Lamps in the Home, ILLUMINATING ENGINEERING, Vol. 42, pp. 365-376, March 1947.

14. E. F. Weinberger, G. A. Roca, RF Shielding of Fluorescent Lamps, ELECTRICAL MANUFACTURING, Vol. 64, pp. 189-190, Nov. 1959.

15. Radio Interference by Fluorescent Lamps, LIGHT & LIGHTING, Vol. 40, pg. 40, Feb. 1947.

16. Radio Interference Evaluation of Cold Cathode Fluorescent Lighting Installations, Naval Civil Engineering Lab., Port Hueneme, Calif., April 1957, N-301.

17. J. M. Rousseau, Radio Interference from Fluorescent Lamps. ELECTRICAL NEWS & ENGINEERING, Vol. 57, No. 6, pp. 48-49, March 15, 1948.

18. J. H. Campbell, C. L. Amick, Radio Interference from Fluorescent Lamps, ELECTRICAL CONSTRUCTION & MAINTENANCE, Vol. 49, No. 8, pp. 54, 139, Aug. 1950.

19. H. J. J. van Boort, M. Klerk, A. A. Kruithof, Radio Interference from Fluorescent Lamps, PHILIPS TECHNICAL REVIEW, Vol. 20, No. 5, pp. 135-144, 1958-9.

"Radio reception, particularly of weak stations in the medium-wave band, is sometimes subject to interference from high frequency oscillations generated in fluorescent lamps and entering the receiver via the mains. Quantitative information on this irregular phenomenon is obtained with a standard test arrangement, the results being analyzed statistically. The authors describe an investigation on this basis into the strength of the interference penetrating into the mains with various types of lamps and ballasts. They indicate what they believe to be the cause of the interference and discuss some methods of reducing its penetration into the mains."

20. C. S. Young, Radio Noise from Fluorescent Lamps, EDISON ELECTRICAL INSTITUTE BULLETIN, Vol. 12, pg. 59, Feb. 1944; POWER PLANT ENGINEERING, Vol. 48, pp. 105-6, Dec. 1944.

Describes measurements of radiation from a filtered and unfiltered 15 watt desk lamp. Indicates that the most important source of interference is radiation from and conduction along supply lines.

21. G. Walters, Suppression of Radio Interference in Fluorescent Lighting Installations, ILLUMINATING ENGINEERING, Vol. 49, No. 6, pp. 295-300, June 1954.

22. J. N. Aldington, Suppression of Radio Interference from

Mains Voltage Fluorescent Lamps, ELECTRICAL TIMES, Vol. 105, No. 2748, pp. 716-719, June 22, 1944.

23. Tests Indicate Interference Levels Generated by Fluorescent Lamps, U. S. BUREAU OF SHIPS JOURNAL, Vol. 3, No. 6, pp. 33-35, Oct. 1954.

In the whole series of measurements (150 kc - 27 mc) the interference levels generated by the instant start lamps were considerably higher than those generated by the filament type lamps. This was true for both radiated and conducted interference levels.

CHAPTER V

POWER LINE INTERFERENCE

It is a well established fact that corona discharge is a source of power line interference with radio reception. A. S. Denholm points out in ref. (39) that the relationship between corona and radio interference was examined in the early 1930's. However the cause of interference was not apparent until G. W. Trichel in the latter half of the 1930's found the pulse forms that could be present in the corona discharge. Trichel showed in ref. (32) that the discharge from a negative point contained fast, regular pulses which increased in frequency as the voltage was raised. Trichel also reported in ref. (33) on the first measurements of the pulses present in positive point corona. Two forms of pulses exist in positive point corona, burst and streamer pulses. Severe interference is normally associated with the streamer pulses, but both positive and negative point corona can cause interference.

A-c and d-c corona characteristics are discussed by G. R. Slemon in ref. (41). Slemon points out that it is necessary for a certain critical voltage gradient to exist before ionization (or corona discharge) can take place. The gradient required for a conductor of radius r in air is given by

$$g_c = 29.8\ K\left[1 + \frac{0.31}{\sqrt{Kr}}\right] \quad \text{kv/cm.} \qquad \text{Eq. 1}$$

where $K = \dfrac{3.92b}{273 + t}$

b = pressure in millimeters of mercury

t = temperature in degrees centigrade

The voltage which will produce this surface ionizing gradient is given by

$$e_c = g_c r \frac{(s-r)}{(s+r)} \cosh^{-1}\left(\frac{s}{r}\right) \text{ kv peak} \qquad \text{Eq. 2}$$

where s = spacing from conductor center to ground plane in centimeters.

Slemon also reported that once the critical voltage gradient, or corona threshold voltage, had been reached the radio noise increased almost linearly with an increase in supply voltage. Radio noise, audible noise, and visible light were all observed simultaneously at the corona threshold voltage. Typical curves of radio noise are given in Fig. V - 1.

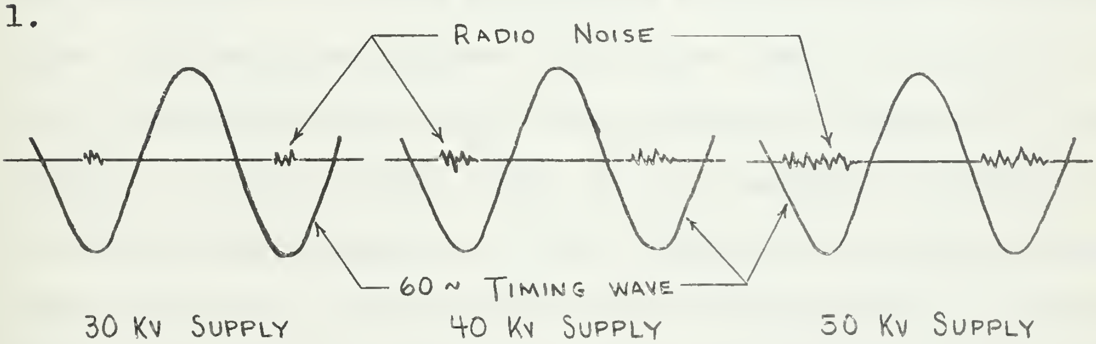

Fig. V - 1 Typical Curves of Increased Radio Noise as Supply Voltage is Increased

The 60 cycle timing wave is in phase with the supply voltage.

Slemon noted that when a positive direct current was applied to a line, no radio noise was observed until approximately twice the a-c corona threshold voltage was reached. With a negative d-c voltage applied, radio noise was again observed only after the a-c corona threshold voltage had

been exceeded by a considerable amount. A typical pattern of negative d-c radio noise is shown in Fig. V - 2.

Fig. V - 2 Waveform of Radio Noise Generated by 50 kv Negative d-c Voltage

In general, the waveform appears to be a mixture of pulses of random amplitude. Repetition frequencies increase with increased voltage.

In ref. (11), S. B. Griscom, et al, present a very plausible explanation for the varying amplitudes, pulse widths, and random repetition rates. They point out that the radio noise which is measured at any one point will be the resultant of corona discharges at many points along the line. The sharpest pulses, with rise times in the order of 0.01 microsecond and decay time constants of about 0.1 microsecond, are those which occur in the immediate vicinity of the measurement location. Other pulses with longer rise and decay times and smaller amplitudes are the result of corona pulses which occurred at other locations and have been deformed in shape and attenuated by traveling along varying lengths of line.

Equations (1) and (2) above show some of the factors that affect corona discharge and levels of power line interference. These are air pressure, temperature, conductor radius, and conductor spacing. Other factors which influence radio noise on power lines are precipitation, contamination

of lines, and conductor configuration.

With the trend toward higher voltage transmission lines, the voltage effect on RI (radio influence) is becoming more important every year. A typical plot of RI field intensity versus phase-to-phase voltage is given in Fig. V - 3. This was extracted from ref. (43).

All references which were reviewed also indicated that radio influence from corona is highest at lower frequencies. Typical plots of RI versus frequency, again taken from ref. (43), are shown in Fig. V - 4.

Many reports on studies of the effects of precipitation on radio noise were reviewed. Typical results are presented by J. Kaminski, et al, in ref. (14). In general, it can be seen in Fig. V - 5 that wetting of conductors decreases the corona threshold voltage by a factor of three or four. Kaminski states that RI levels may be increased by factors of four to 25 by wetting conductors.

In ref. (68) the Hinchman Corporation reports that the interference level caused by snow is dependent upon the wetness of the snow. Similarily, interference levels of transmission lines operating in fog would depend upon the amount of condensation upon the conductors. In general, higher relative humidity would cause greater condensation and more interference.

The presence of contaminants, such as salt spray deposits, also affects RI levels. According to W. A. Hillebrand

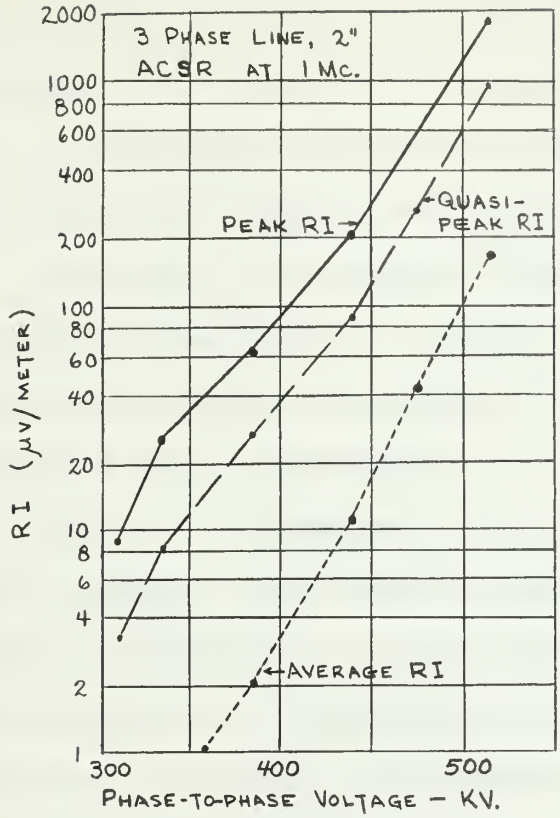

FIG. V - 3. TYPICAL RI FIELD INTENSITY VS. ϕ-ϕ VOLTAGE

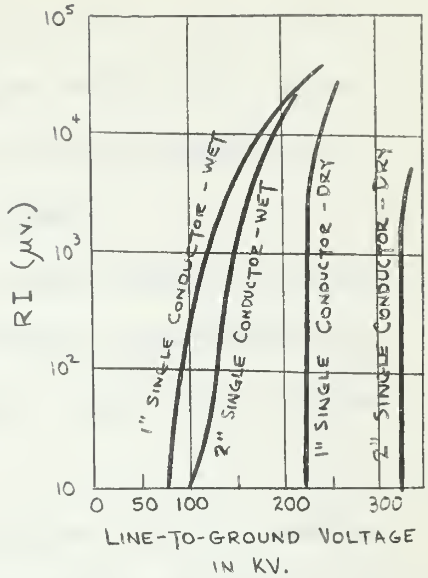

FIG. V - 5. TYPICAL EFFECT ON RI CAUSED BY WETTING OF CONDUCTORS.

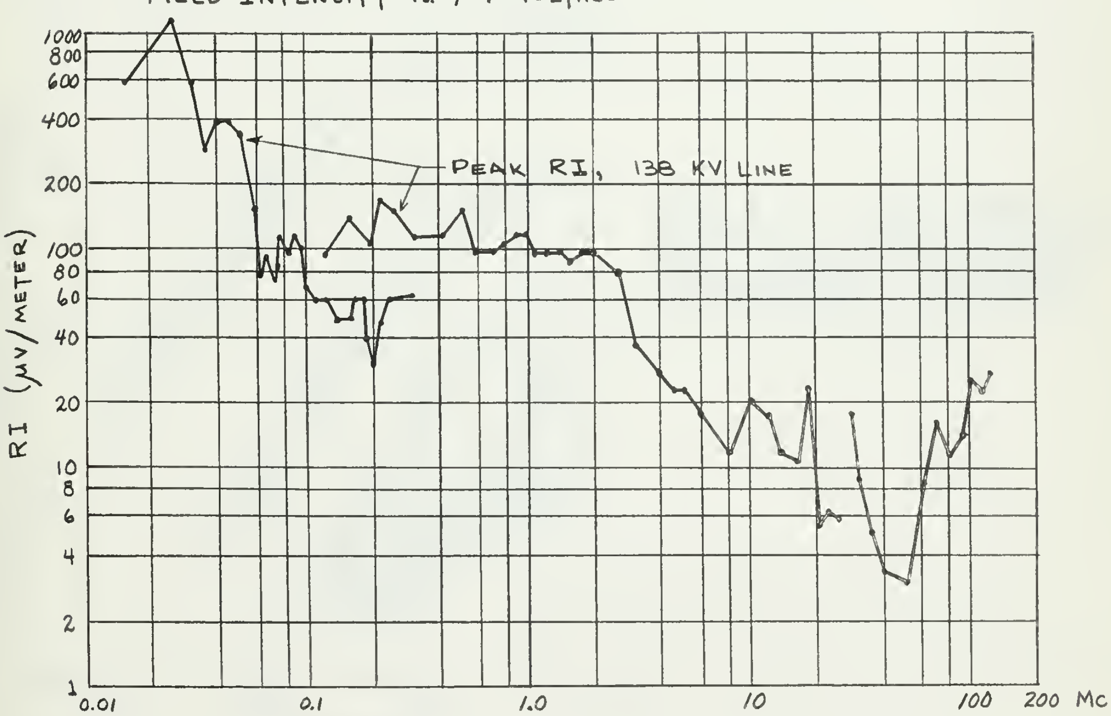

FIG. V - 4. TYPICAL RI FIELD INTENSITY VS. FREQ.

and Charles J. Miller, Jr. as reported in ref. (23), the presence of a contaminant increased the radio noise from zero to 4250 microvolts in one laboratory experiment in which all other factors were held constant.

The effect of conductor diameter upon radio noise can be seen in equation (2). Smaller diameter conductors require less voltage for corona discharge; therefore, higher RI levels can be expected.

Fig. V - 6, from ref. (40), shows that bundle conductors in general have higher corona threshold voltages as the number of conductors is increased. The RI field intensity also decreases as the number of conductors in the bundle is increased. The major disadvantage in using bundled conductors is higher initial cost.

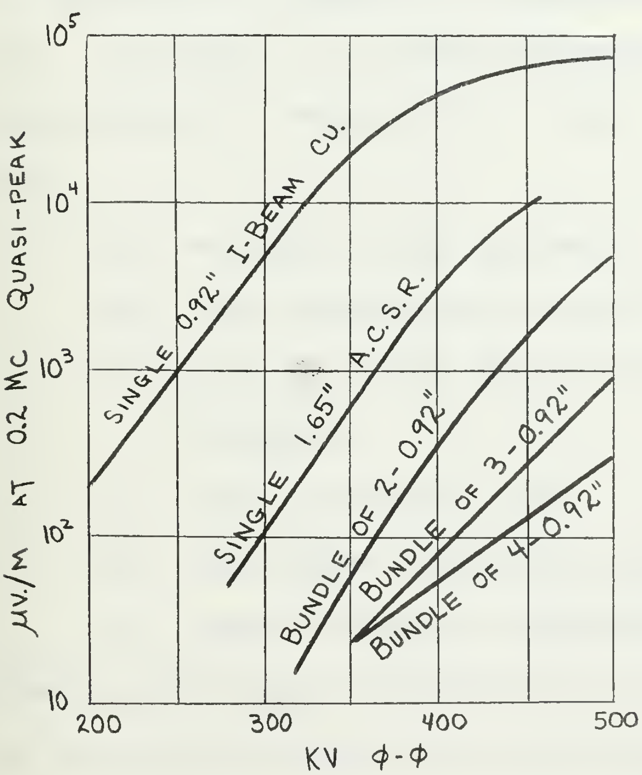

Fig. V - 6 RI Intensity Variation With Voltage In Fair Weather For Single and Bundled Conductors

From equation (2) one would conclude that a reduction in separation between conductors would decrease the corona threshold voltage. thereby increasing radio noise. In ref. (68) the Hinchman Corporation relates that this is true between conductors and between conductors and ground; however, it appears that the field pattern is disturbed to such an extent that r-f noise transverse to the conductors is decreased. This was confirmed in field tests by the Bonneville Power Administration in 1946. These same tests showed that decreasing the height above ground of conductors also decreased radio noise.

The cure to power line interference problems should start with good system design. Present day techniques make it possible to predict RI levels before a line is constructed. In 1940, L. V. Blake proposed six practical construction rules for reducing RI. These rules, given in ref. (38), are:

(1) Maintain tight hardware:

(2) Keep ground wires clear of ungrounded hardware:

(3) Keep guy wires clear of all other wires and hardware;

(4) Keep tie wires tight:

(5) Use proper insulators and pins;

(6) Remove "haywire" found hanging on line wires.

However additional techniques are used today. One technique is the use of shields over insulators to eliminate

contamination, thereby reducing arcing. Refs. (9) and (35) describe such shields. Ref. (12) illustrates a corona shield that may be used on suspension assemblies. Ref. (8) describes how adherent conductive coatings were used to cover insulators and increase the corona threshold voltage, thus reducing RI.

Thus far in this chapter only radio noise generated by a power line and its associated hardware has been considered. Other sources of power line interference are possible and, in many cases, are even more serious a problem. Transmission lines may act as antennas and pick up electromagnetic energy from a variety of radiating sources, conduct that energy long distances and then reradiate the energy or conduct it to the power supply of a piece of equipment. Reradiation is normally not too serious because at relatively short distances (several hundred feet) from the line the interference intensity is negligible. The elimination of conducted interference is covered in Chapter XI, Suppression. A relatively new method of attacking both the reradiated and conducted interference problem is discussed in ref. (16) by D. B. Clark and J. L. Brooks. They describe tests on a four mile, 13.2 kv, three phase power line which utilized conventional conductors wrapped with a high-permeability tape. Broad-spectrum (30 cps to 1 kmc) electromagnetic interference which was induced at one end of the line was attenuated within two miles to bring the line noise level down to the

natural ambient level. Radiated field intensity decreased at a rate greater than the inverse square of distance from the line.

CHAPTER V
BIBLIOGRAPHY AND ABSTRACTS

1. C. E. Mercier, W. E. Elliott, Analysis and Elimination of Corona Effects, ELECTRICAL MANUFACTURING, Vol. 60, pp. 140-45, Nov., 1957.

2. D. C. Ports, Analysis of Radio Frequency Interference in Transmission Lines and Filters, ELECTRONIC INDUSTRIES, Vol. 19, pp. 93-100, July 1960.

3. G. E. Adams and L. O. Barthold, Calculation of Attenuation Constants for Radio Noise Analysis of Overhead Lines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 79, pp. 975-81, Dec. 1960.

   A general procedure for calculating attenuation constants for radio noise, using Maxwell's equations, are given. The contributions to attenuation of various line parameters are clarified. Comparisons of calculated and measured attenuation constants are given.

4. G. E. Adams, Calculation of Radio Interference Level of Transmission Lines Caused by Corona Discharges, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 75, pp. 411-18, June 1956.

5. W. A. Schulz, Can Radio Noise from Loose Hardware be Eliminated?, ELECTRIC LIGHT AND POWER, Vol. 15, pp. 59-60, Oct. 1937.

6. C. J. Miller, Jr., Characteristics of Smooth Bundled Conductors, ELECTRICAL ENGINEERING, Vol. 75, pg. 598, July 1956.

   This article describes laboratory experiments carried out to determine corona and radio-interference characteristics of bundled conductors. Comparisons are made with theoretical calculations.

7. D. B. Clark, R. D. Hitchcock, Contiguous Wrapping of Transmission Line Conductors with High-mu Tape for Large Radio Interference Attenuation, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 560-77, Oct. 1959, (AD-235 873).

   "This paper describes the application of a high-permeability SiFeMg tape to a transmission line,

resulting in high attenuation of radio-frequency energy in the range of interference frequencies found normally on transmission lines. A theoretical treatment is presented of a long conductor coated with a high-permeability material. The results of this analysis show a great magnification of the skin effect losses at frequencies above the power transmission frequency, and are supported by experimental measurements made on three long conductors wrapped with a thin, high-permeability tape. A small helical air gap was formed in the wrapping of two of the transmission lines to reduce saturation effects which would normally occur on lines distributing power. The attenuation measured on these lines was about half that of the fully wrapped line, but gave much lower standing wave ratios and a low characteristic impedance phase shift. The attenuation of these lines was large compared to the attenuation of a bare line. It is expected that high-permeability tape coatings with a gap will prove to be useful and practical technique for reducing interference on power transmission lines."

8. Edward Bennett and G. L. Fredenhall, Control of Potential Over Insulator Surfaces, ELECTRICAL ENGINEERING, Vol. 54, pp. 1084-87, Oct. 1935.

   "To reduce radio interference caused by corona from pin insulators, adherent conducting coatings or films usually are applied to the central portions of the heads of the insulators, and metal thimbles or conducting coatings in the pin holes. By extending the coating to cover the entire head and by using a coating of the proper resistivity, the voltage at which corona occurs can be raised considerably without materially lowering the flashover voltage. This paper calls attention to the principle of controlling the potential distribution over surfaces of insulators by utilizing the resistance drop in potential resulting from the flow of charging current in high resistance films."

9. A. A. Milusich, Corona Shields Prevent RI on 138-kv Bus, ELECTRICAL WORLD, Vol. 148, pg. 70, Aug. 5, 1957.

   This short article describes and shows pictures of corona shields which were installed by a New York power company.

10. W. E. Keever, Cut Loose from Chaos: Power Line's Effect on Reception, RADIO NEWS, Vol. 24, pg. 38, July 1940; Vol. 24, pg. 5, Aug. 1940.

11. S. B. Griscom, R. H. Schlomann, D. F. Shankle, E. R. Taylor, Jr., Decoupling of Transmission Lines to Radio-Influence Voltage, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems) Vol. 79, pp.1066-73, Feb. 1961.

This article reviews the theory of the generation of radio frequency voltages by corona discharges on transmission lines. The purpose, configuration, and method of operation of the decouplers are given. Laboratory and field tests results are reported.

12 J. Kaminski, Jr., Development of Corona Shields for Suspension Assemblies of Bundled-Conductor Transmission Lines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 77, pp. 89-93, April 1958.

This article reports on studies made to determine the corona-onset voltages and RIV (radio-influence voltage) on various appurtenances for supporting bundled conductors in a 345-kv system. Descriptions of and results of tests on unshielded bundled-conductor assemblies, and shielded single-string and double-suspension-string bundled-conductor assemblies are given. The reduction of RIV by use of corona shields on suspension assemblies is also reported.

13. C. V. Aggers, W. E. Pakala, W. A. Stickel, Effect of Radio Frequencies of a Power System on Radio-Receiving Systems, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 62, pp. 169-72, April 1943.

"This paper is concerned with high-voltage apparatus and describes tests and methods for calculating the over-all effects on radio reception resulting from the radio-frequency voltages produced incidentally by power apparatus. The calculations depend upon a number of factors for some of which the range and probable values have not been determined. One of these factors for which information is required is the coupling factor of antenna to power lines and is defined as the ratio of field intensity at the radio listener's antenna to the field intensity under or near the transmission line. To determine this coupling factor, field tests were made at radio frequencies in a city receiving power from 25-kv transmission lines and 4-kv distribution circuits. A radio-frequency generator was connected to the 25-kv bus at the substation, and field-

intensity measurements were made near the power lines and at 29 receiver antennas located at various distances from the 25-kv lines. The coupling factors to the nearest power circuit and to the 25-kv line were thus obtained for all the antennas tested. Various other data useful in radio coordination were obtained. These include equivalent effective height of outdoor antennas used by radio listeners, types of grounds and distances from antenna to high-voltage and low-voltage lines."

14. J. Kaminski, B. E. Kingsbury, F. C. Vose, Effect of Rain on RIV Characteristics of High-voltage Suspension Assemblies, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3, (Power Apparatus and Systems), Vol. 78, pp. 669-71, Aug. 1959.

    The article describes results of laboratory tests made to determine the increase in RIV due to wetting of transmission cables and suspension assemblies. All tests were performed with a line-to-ground voltage of 219 kv with the RIV being measured at 1000 kc. The effects of different suspension assemblies, different cable sizes, and addition of corona shields are investigated.

15. A. S. Denholm, Electric Stress Grading of Insulator Strings and Their Radio Influence Voltages, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Pt. 3 (Power Apparatus and Systems), pp. 167-73, June 1960.

16. D. B. Clark, J. L. Brooks, Evaluation of the Interference-Suppressing Power Conductor, Naval Civil Engineering Laboratory, Port Hueneme, Calif., Dec. 20, 1961, Technical Rpt. No. 178, (AD-268 730).

    "Field evaluation was made of a 4-mile installation of 13.2 kv, 3-phase, special interference-attenuating power line. The special line, with large magnitudes of interference at its beginning, is shown to attenuate effectively over the broad frequency spectrum to bring the noise level of the line down to the level of the natural ambient in about half of its length. Impedance measurements of the power line as a transmission line showed it to be independent of line terminations, and that considerable attenuation was present. Field intensity measurements showed that the intensity decreased rapidly in greater than inverse square with distance, indicating a field propagated along the line, with no measurable radiation away from the line. The effect of the high-permeability tape thickness on attenuation is

considered theoretically and experimentally, and it shows that attenuation is proportional to the tape thickness until the thickness is of the order of one skin depth. The potential applications and limitations of the new interference-suppressing line are presented.

17. B. V. Smirnov, Formulation and Structure of Noise in Overhead Electric Networks at 0.5 - 35 kv, translated by L. A. Fenn, TELECOMMUNICATIONS, No. 7, pp. 813-25, 1960.

"It is proved that in aerial lines at 0.4 - 35 kv the principal sources of noise in the range 0.05 - 155 kc are the generators and transformers with their non-linear volt-ampere characteristics and the insulators which form partial discharge impulses. The structure and magnitude of the noise from these sources is considered." The effect of rain and fog on noise levels is also presented.

18. S. Whitehead, W. G. Radley, Generation and Flow of Harmonics in Transmission Systems, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, Vol. 96, pp. 29-48, part 2, Feb. 1949.

"The paper deals with the magnitude and distribution of harmonic currents flowing in a.c. networks. The various sources of harmonics are discussed in general, and harmonics arising from the use of mercury-arc rectifiers and in h.v. transmissions are dealt with in greater detail.
"The flow of harmonics arising from these sources is considered from a theoretical aspect, using equivalent networks, experimental verification of these theories being given for certain simple cases. The possibilities of a complete theoretical solution is shown, and certain probable practical conclusions are drawn.
"Various methods of reducing harmonics are discussed, and the relative importance of the various sources is considered in the light of modern trends in harmonic suppression."

19. J. McCombe, High Voltage Lines and G. P. O. Circuits - Separating Distances Stipulated, ELECTRICAL REVIEW. Vol. 123, Pg. 678, Nov. 11, 1938.

20. J. S. Crooks, H. A. Baldwin, L. E. Bates, Improved Hardware Cuts Radio Interference, ELECTRICAL WORLD, Vol. 116, pg. 66, July 12, 1941.

This article gives a case history of the construction of a power line and its subsequent cause of RI. The RI was traced to hardware. The changes in construction specifications and the corrections made on existing lines are given.

21. F. L. Greene, Improving Radio and Television Influence of Power Circuits, Proceedings of American Power Conference, Vol. 19, pp. 552-57, 1957.

"Improvements in the operation of power circuits to lessen radio and television interference have been brought about by developments in corona control, pin-type insulators, wood pole line hardware, insulated neutral supports, insulation, static-proof hardware, the use of spring washers, distribution equipment, dead-end assemblies, post-type insulators, insulator tie-wire and distribution fused breakers. The methods followed under all these headings are discussed and the importance of reducing radio interference is emphasized."

22. Paul Shoup, Insulated Stick Solves Some Interference Woes, ELECTRICAL WORLD, Vol. 154, pg. 97, Nov. 21, 1960.

This short article describes the method used by the Ohio Power Company to locate specific sources of RI. A telescoping hot stick is used to move hardware and lines.

23. W. A. Hillebrand, Charles J. Miller, Jr., Insulator Surface and Radio Effects, ELECTRICAL ENGINEERING, Vol. 53, pp. 1213-20, Aug. 1934.

Investigation of the effects of dirty and wet insulators on RI is reported. Both laboratory and field tests were made. Tables are presented which show the effect of varying humidity, insulator covering and electrode shape.

24. J. B. Bowen, Insulators Salvaged by Cadium Plating; Reduction of Radio Interference, ELECTRICAL WORLD, Vol. 106, pg. 2835, Sept. 12, 1936.

This article describes how corrosion of suspension type insulators cause RI from a power line in southern California. The method of rehabilitating hardware by cadmium plating is described.

25. H. R. J. Klewe, Interference Between Power Systems and Telecommunication Lines, Edw. Arnold, Ltd., Publishers, London.

26. J. S. Forrest, Interference from Power Lines, WIRELESS WORLD, Vol. 49, pp. 128-31, May 1943.

27. D. B. Wright, Interference Sources and Effective Reduction Procedures for Power Line Interference, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 302-14, Feb. 1957.

"This paper, a current review of the power line interference reduction problem, presents the more common sources of power line interference, methods of propagation, and some applicable reduction procedures. The use of lumped circuit elements and distributed circuit elements in power line filters is discussed. Experimental data illustrating typical power line interference levels and the effectiveness of lumped and distributed filter elements are presented and discussed."

28. H. L. Rorden, R. S. Gens, Investigation of Radio Noise as It Pertains to the Design of High-Voltage Transmission Lines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 71, pp. 466-81, Jan. 1952.

The effects of conductor diameter, spacing, height above ground, and rain upon lines is considered. The method of generation and intensity of radio noise is discussed. Laboratory tests and tests on several 230 kv lines of the Bonneville Power Administration are reported.

29. H. N. Kalb, Isolating Radio Interference, ELECTRICAL WORLD, Vol. 105, pp. 36-7, March 2, 1935.

This article describes how a two mile section of an 11 kv power line passing a commercial Trans-Pacific radio-receiving station was isolated from radio interference originating in the rest of the line. Attenuation coils in the line and choke coils in transformers were used.

30. J. C. Senn, Laboratory and Field Tests on Risco Radio Interference Choke Coils for Overhead Power Lines, Naval Civil Engineering Laboratory, Port Hueneme, Calif., Dec. 26, 1956, Technical note no. N-282, (AD-221 766L).

"Results are given for tests made on actual installations on public utility power lines equipped with RISCO radio interference choke coils. In addition, results of laboratory insertion loss measurements are reported. It is concluded that the coils, if

properly installed are effective over a frequency range roughly equal to the standard broadcast band. At higher frequencies, effectiveness is drastically reduced by the inter-turn capacitance of the coils. It is recommended that choke coils designed for a specific frequency range be used where serious power line interference is occurring in that specific band of frequencies."

31. James Evans, James O'Day, Low-Frequency Anomalies Due to Man-made Electrical Conductors, Willow Run Laboratories, Univ. of Michigan, Ann Arbor, July 1959, (AD-219 852).

"Anomalies in the hyperbolic field of a low-frequency navigation system occur in the vicinity of man-made electrical conductors. Rather large effects can be expected when the system operates very close to long telephone and power lines. A short series of experiments was conducted in the service area of a Bendix-Decca chain in southwestern United States to investigate the extent of these anomalies. Data were obtained on the ground, and several airborne runs were made to determine the extent in altitude of such anomalies. It was concluded that, although errors in the immediate vicinity of man-made re-radiators on the ground may frequently be as great as $\frac{1}{2}$ wavelength and that such errors are extremely difficult to eliminate by calibration from any operational system, the effect at altitudes greater than 50 ft. (from the anomaly-producing object) is negligible; therefore, anomaly-producing objects of the type investigated present no great problem in the navigation of drone aircraft."

32. G. W. Trichel, The Mechanism of the Negative Point-to-Plane Corona Near Onset, PHYSICAL REVIEW, Vol. 54. pp. 1078-84, Dec. 15, 1938.

33. G. W. Trichel, The Mechanism of the Positive Point-to-Plane Corona in Air at Atmospheric Pressure, PHYSICAL REVIEW, Vol. 55, pp. 382-90, Feb. 15, 1939.

34. M. Jenssen, On Radiation from Overhead Transmission Lines, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, pt. 3 (Radio and Communications Engineering), Vol. 97, pp. 166-78, May 1950.

"The general problem of radiation from lines is discussed and the theoretical background is sketched. The radiation is calculated by the usual approximate method, i.e., the current distribution of the principal wave in an infinite line is first determined,

and the radiation field of a finite line is then calculated on the assumption that the current distribution is the same. The method is applied to lines in free space, to single-wire lines above earth of finite conductivity (earth-return line) and to multiple lines above earth of finite conductivity. The current distribution and possible wave types in some typical multiple-lines are analyzed. It is shown that only the wave in the earth-return line, and the corresponding wave type in the multiple line, will produce appreciable radiation. Formulae for calculation of this radiation field are given, and experimental results are described. Conclusions are drawn regarding interference in carrier-line systems and the use of long-wire transmitting antennae."

35. C. M. Wagner, Plastic Shields for Insulators Stop Flashovers, ELECTRICAL WORLD, Vol. 149, pg. 61, March 10, 1958.

"Plexiglas and other plastic shields are illustrated and described which have been used to eliminate salt spray and dirt contamination on insulators, thereby reducing arcing."

36. R. M. Smith, Power-line Noise, QST, Vol. 43, pp. 26-29, Nov. 1959.

A narrative is given of a ham operator's experience in detecting and locating a source of interference. With cooperation from the power company, the RFI was eliminated.

37. J. C. Senn, D. C. Wright, A Practical Handbook for Location and Prevention of Radio Interference from Overhead Power Lines, Naval Civil Engineering Research and Evaluation Laboratory, Port Hueneme, Calif., Nov. 21, 1956, Technical memo. no. M-116, (AD-125 060).

"This Handbook is written primarily for the use of Public Works personnel responsible for the design, construction, and maintenance of overload power distribution systems which must be free of electromagnetic interference. It describes in nontechnical terms the common causes of power line interference and lists practical measures required for the location and elimination of these causes."

38. L. V. Blake, Prevention Easier than Cure of Radio Interference, ELECTRICAL WORLD, Vol. 114, pp. 851-53, Sept. 21, 1940.

The author gives six general construction rules to be followed in designing and erecting distribution lines that will eliminate the common sources of radio interference.

39. A. S. Denholm, Pulses and Radio Influence Voltage of Power-Frequency Corona, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 79, pp. 698-707, Oct. 1960.

The author reviews the history of the study of corona discharge and describes the start of an investigation to examine corona pulses which occur with alternating voltages on short lengths of conductor. Test procedures are described and results are discussed.

40. G. D. Lippert, et al, Radio-Influence Characteristics of Bundle and Single Conductors, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 76, pp. 1302-8, Feb. 1958.

This paper reports on tests conducted on bundle and single conductors to determine radio influence voltage levels. Corona loss and radio influence are compared. The variations of RI with weather, frequency, voltage, and bundle size are considered.

41. G. R. Slemon, Radio Influence from High-Voltage Corona, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 1, Vol. 68, pp. 198-204, 1949.

A-c and d-c corona characteristics are discussed. Effects of conductor spacing, frequency, wetting, and dirt are considered.

42. G. S. Smith, A. B. Jacobsen, Radio Influence from Power Transmission Lines - Effects of Wind, Dust and Smoke, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 71, pp. 932-38, Oct. 1952.

Tests conducted in a wind tunnel indicated that wind, dust, and smoke had very little effect on RI.

43. W. E. Pakala, C. D. Fahrnkopk et al, Radio Influence from Transmission Lines, WESTINGHOUSE ENGINEER, Vol. 11, pp. 190-195, Nov. 1951.

Laboratory tests and field tests were conducted to develop data for predicting RI characteristics

from transmission lines. Parameters affecting RIV which are considered are weather, aging, line voltage, conductor diameter, bundles, line length, and phase of line.

44. G. D. Lippert, et al, Radio-Influence Test in Field and Laboratory - 500 kv Test Project, ELECTRICAL ENGINEERING, Vol. 70, pp. 481-86, June 1951.

A study of radio influence on a 500 kv test line is reported. The effects of weather, precipitation, variations in voltage, frequency, and conductor diameter were all investigated.

45. R. E. Graham, C. R. Bond, Radio-Influence Testing on 70 Miles of 345-kv Horizontal Bundle Conductor, ELECTRICAL ENGINEERING, Vol. 80, pp. 854-859, Nov. 1961.

A description is given of RI level tests conducted on two sections of the line. Effects of precipitation are noted and attenuation tests are made.

46. T. W. Liao, Radio Influence Voltages Caused by Surface Imperfections on Single and Bundle Conductors, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 78, pp. 1038-1046, Dec. 1959.

The experimental setup and test procedures are described for tests to determine RIV on high voltage lines. Protrusions from conductors are determined to be the source of RIV. Results are presented graphically for single conductors and various configurations of bundled conductors.

47. L. N Stone, R. S. Gens, E. H. Gehrig, Radio Interference Attenuation on Energized High-Voltage Transmission Lines: Measurement and Application, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 78, pp. 1238-1247, Dec. 1959.

This paper proposes a method for predicting the additive effect of individual sources of RFI on a line and reports the attenuation of these sources on a high voltage transmission line. Experimental values of RIV are compared with calculated values.

48. Radio Interference from A-C Conductor Corona, ELECTRIC WEST, Vol. 74, pg. 21, May 1935.

49. R. L. Tanner, Radio Interference from Corona Discharges,

Stanford Research Institute, Technical Rept. 37, April 1953, (AD-12 600).

50. K. Ia. Kafieva, Radio Interference from Corona on Transmission Lines, ELECTRIC TECHNOLOGY USSR, Vol. 8, pp. 598-612, 1960.

The paper contains the results of investigation into interference from corona on transmission lines in the U. S. S. R. Various factors considered are precipitation, relative humidity of air, air density, state of conductor surfaces, line design features, and frequency.

51. J. L. Langton, E. Bradshaw, Radio Interference from Discharges on High-Voltage Line Insulators, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 75, pp. 643-52, Nov. 1934.

"Experimental work was performed to determine the relative amount of interference caused by discharge on line insulators due to their configuration, to the atmospheric conditions, and to pollution of the insulator surfaces. Control of conditions such as humidity was obtained by investigations within a glass-sided chamber. The cap-and-pin type insulator was most free from discharges, but methods of reducing the discharges considerably were found for the pin-type insulator by means of metal inserts to the binder or by the use of metal caps; and for the interlink-type insulator by using large links and compound lining. Field tests were made to verify the conclusions reached from the laboratory work. Several points of agreement were noted."

52. S. F. Pearce, Radio Interference from High Voltage Distribution Systems, British Electrical and Allied Industries Research Association, Technical Rept. M/T 122, 1954, (released 1957).

53. C. H. W. Clark, Radio Interference from H. V. Insulators, ELECTRICAL REVIEW, Vol. 165, pp. 491-97, Oct. 23, 1959.

The author explains the mechanism of interference generation by high-voltage insulators and the effect of insulator design on radio interference. The measurement of interference is considered and methods of overcoming the difficulties involved are discussed.

54. W. Furbert, Radio Interference from H. V. Lines, ELECTRICAL REVIEW, Vol. 116, pg. 689, May 10, 1935.

55. R. J. Mather, B. M. Bailey, Radio Interference from High Voltage Lines - Part I, Statistical Approach, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 80, pp. 890-94, Dec. 1961.

Since noise varies, the authors utilize statistical methods to predict its level. Half-hourly readings for a one year period were analyzed and random sampling techniques applied to this data.

56. G. E. Adams, Radio Interference from High-Voltage Transmission Lines as Influenced by the Line Design, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), pp. 54-62, April 1958.

The author contends that proper design is the only effective way to control the interference level of a line. The calculations of interference levels are effected by the following principal design items: vertical versus horizontal configuration, interphase spacing, center-to-center spacing between conductors of a bundle, and conductor phasing and circuit separation for double-circuit lines. The effect of attenuation along the line on the interference level is derived and discussed in terms of its effect upon the various modes of propagation.

57. F. O. McMillan, Radio Interference from Insulator Corona, ELECTRICAL ENGINEERING, Vol. 51, pg. 3, Jan. 1932.

58. G. E. Adams, Radio Interference of Bundled Conductors, ELECTRICAL ENGINEERING, Vol. 76, pg. 37, Jan. 1957.

The interference levels of single, dual, and triple conductors of different diameters are compared.

59. L. J. Corbett, Radio Interference Problem and the Power Company, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS JOURNAL, Vol. 44, pg. 1057, Oct. 1925.

60. J. Reichman, J. R. Leslie, Radio Interference Studies on Extra-High-Voltage Lines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 80, pp. 261-70, June 1961.

This paper describes RIV tests on 600 kv, 2500 ft., 4-conductor, 1.1 and 0.8 inch diameter conductor

lines. Tower proximity and insulator and hardware effects on corona are discussed.

61. H. L. Rorden, Radio Noise Influence of 230-kv Lines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Technical Paper 47-92, 1947.

Considerations are given to conductor diameter and spacing, insulation level, and radio interference. Due to wartime shortages, design changes had to be made.

62. G. E. Adams, et al, Radio Noise Propagation and Attenuation Tests on Bonneville Power Administration McNary-Ross 345-kv Line, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS pt. 3 (Power Apparatus and Systems), Vol. 78, pp. 380-87, June 1959.

A program to determine the attenuation for the different modes of propagation for this extra-high-voltage line is discussed. Results are compared with theoretical calculations.

63. R. D. Iden, Radio-Proof 24-kv Urban Line, ELECTRICAL WORLD, Vol. 114, pg.1182, Oct. 19, 1940.

Radio-proof insulators and pins were used in the construction of a power line through a densely populated residential area.

64. Reduction of Power Line Radio Interference, U. S. BUREAU OF SHIPS JOURNAL, Vol. 5, pg. 32, Feb. 1957.

See following reference for abstract.

65. J. C. Senn, A. W. Gosley, Reduction of Power Line Radio Interference, Naval Civil Engineering Laboratory, Technical memo M-095, Feb. 1, 1955, (AD-81 139).

This report is a discussion of the work done on an isolation filter for reduction of power-line radio interference. Construction details of the filter and subsequent tests are described. Results of tests are tabulated and indicate that in general it is impractical to bury a power line in the earth as a filter.

66. T. W. Liao, W. A. Keen, Jr., D. R. Powell, Relationships Between Corona and Radio Influence on Transmission Lines, Laboratory Studies. I--Point and Conductor Corona, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 76, pp. 530-40, Aug. 1957.

67. T. W. Liao, J. J. Laforest, Relationship Between Corona and Radio Noise on Transmission Lines. 2--Conductor and Insulator Corona, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 3 (Power Apparatus and Systems), Vol. 78, pp. 706-712, Oct. 1959.

The relation of total RI to that caused by corona is discussed. This work extends previous study by the authors to include conductors which are more representative of the types used in EHV lines. Test procedures and results are presented.

68. A Review of Past and Current Work in Electromagnetic Interference Voltage from Electric Power Transmission Lines, Hinchman Corporation, Detroit, Michigan, Nov. 1955, (AD-108 685).

This report covers the theory of RI generation and its association with corona, the effects of conductor voltage, weathering, conductor configuration, frequency, choke coils, and line hardware and insulators. Standards for electromagnetic-interference levels and measurement techniques are also included.

69. C. J. Miller, Jr., Some Insulator Designs Require Special Features to Insure Radio Quietness, ELECTRICAL ENGINEERING, Vol. 60, pp. 62-66, Feb. 1941.

Insulators are considered as a source of radio interference. Design features are discussed which can reduce the radio interference.

70. A. M. Intrator, Some Theoretical Considerations Concerning Radiation from Overhead Transmission Lines, Naval Civil Engineer Research and Evaluation Laboratory, Technical Rpt. R-003, June 28, 1953.

71. F. Conrad, Specification of Interference Producing Property of High Tension Lines, WIRELESS ENGINEER, Vol. 19, pp. 575-76, Dec. 1942.

72. J. C. Senn, Studies Leading to the Development of a Radio Interference Filter for Overhead Power Lines, Naval Civil Engineering Research and Evaluation Laboratory, Technical memo M-117, Jan. 4, 1957, (AD-130 461).

"A unique distributed-loss filter is proposed for radio interference reduction; the filter length provides the necessary decoupling of input and output, and the filter, itself, absorbs the travelling interference energy. A study of possible sheath materials indicated that the best compromise of

electrical characteristics and physical properties would be a thick sheath of carbon-loaded neoprene or rubber similar to the sheath on aerial cable. For a study of the grounding problem and the variation of loss with sheath resistance under actual use, conductive tape was used to simulate the sheath on a 250-ft. filter in a 1000-ft. power line on 50-ft. poles spaced 125 ft. apart. Results showed a general increase in insertion loss as the sheath resistance is reduced with the maximum occurring for 5 layers of tape: the addition of more layers had no significant effect on the loss characteristics. Test and shielded building data indicated that the effective grounding cannot be obtained when the ground lead approaches quarter-wave resonance. The optimum value of sheath conductivity results in improved loss characteristics. Test results with coils indicated that the proper combination of lossy filter and coils should give a good broadband insertion loss characteristic."

73. H. Page, Suppression of Corona and Precipitation Interference in VHF Reception, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, part B, Vol. 108, pp. 469-70, July 1961.

74. P. B. Frost, E. F. H. Gould, Telephone Interference from Power Systems, ELECTRICAL WORLD, Vol. 127, pg. 82, Feb. 1, 1947.

75. J. C. Fear, Transmission Line Interference Cures, ELECTRICAL WORLD, pt. 1, Vol. 113, pg. 450, Feb. 10, 1940; pt. 2, Vol. 113, pg. 598, Feb. 24, 1940.

Three areas where pin-point discharges occur are pointed out and methods of eliminating these discharges are discussed.

76. Transmission: Radio Noise Highlighted, ELECTRICAL WORLD, Vol. 157, pp. 48-50, Feb. 26, 1962.

CHAPTER VI

ELECTRICAL SYSTEM INTERFERENCE

RAILROADS AND TROLLEYS

Although electrified trolleys or trolley busses have nearly disappeared from the American scene, there are still a few in existence as well as numerous sections of electrified railways. Howe, in 1939, ran a series of tests on street railway systems. In ref. (3), he first treats the streetcar itself and then the overhead trolley system. He showed that the installation of capacitance and inductance in the main circuit of the car had two effects: (1) it minimized the interference resulting from circuit interruptions within the car, and (2) it shifted the frequency of the radiated interference out of the broadcast band. It had no effect on the interference conducted by the overhead lines. He further, as a result of tests on the overhead trolley system, made the following observations:

(1) The intensity of the interference is proportional to the magnitude of the current broken until a point is reached when the follow-through arc tends to suppress the rapidity of the break;

(2) Distance along the lines has no effect on the strength of the interference;

(3) The up-lead portion of the test antenna picks up 75% of the interference received.

POWER DISTRIBUTION SYSTEMS

Radio coordination of electric apparatus can be separated into two categories, low-voltage and high-voltage. The low-voltage category is limited to a maximum of 1200 volts and is usually located in close proximity to the radio receiver. The high-voltage category includes the generator, transmission and distribution of electrical power. Rathpletz and Williams indicated in ref. (21) that three major factors must be considered in any problem involving coordination between power and communication circuits:

1. Inductive influence -- those characteristics of an electric supply circuit with its associated apparatus that determine the character and intensity of the inductive field which it produces.
2. Inductive susceptiveness -- those characteristics of a signal circuit with its associated apparatus which determine, so far as such characteristics can determine, the extent to which it is capable of being adversely affected by a given inductive field.
3. Inductive coupling between two circuits -- the interrelation of neighboring electric supply and signal circuits by electric or magnetic induction or both.

In addition, TIF is described as follows:

the telephone influence factor of a voltage or current wave is the ratio of the square root of the sum of the squares of the weighted rms values of all the sine wave components (including both fundamental and harmonic) to the rms value (unweighted) of the entire wave. The term I x T is defined as the product of a current wave and equals the product of the magnitude of the current wave in amperes (rms value unweighted) times its TIF. Investigation of interference problems on rural power and communication lines revealed the following: 1. Transformers with a designed I x T product of 15 or less per KVA on a 120 volt base presented no interference problems; 2. Generators with an undistorted wave

shape having an open circuit TIF of less than 15 would not cause interference problems; 3. Some lengthy lines approached one-quarter wave resonancy at audible frequencies creating serious noise problems. This was reduced by the use of a device in each phase matching its impedance to that of the line.

Foust and Frick reported in ref. (15) that radio interference intensity increased with:

(1) Increased applied voltage;

(2) Increased number and extent of field voltage gradients concentrated at particular points of small radius of curvature on the test piece or test circuit;

(3) A decrease in humidity.

They also determined that radio influence voltage varies with time of voltage application, particularly within the first few minutes. For example the interference generated by an insulator decreased rapidly at first and then slowing, reached a constant value in about 20 minutes.

Aggers, Pakala, and Stickel stated in ref. (9) that the following factors must be taken into consideration in a radio-coordination problem:

(a) Broadcast station field intensity in microvolts per meter
(b) Signal to noise ratio acceptable to the radio listener
(c) Ratio of interference field intensity at antenna to value at high voltage line
(d) Ratio of radio influence voltage on line to field intensity under or near the line
(e) Ratio of radio influence voltage measured with a standard laboratory-test circuit to voltage which will appear on line when apparatus is connected

(f) Effect of service conditions.
The above factors can be expressed in the form of an equation

$$RIV = \frac{ade}{bcf}$$

where RIV is the radio-influence voltage referred to the standard high-voltage test circuit. If we use 31.6 (30 db) for b, 70 for d, 2.42 for e, and 1 for f -- all of which are reasonable values -- and change nomenclature for broadcast field intensity from a to E, then the equation may be written

$$RIV = \frac{5.36\ E}{C} \text{ microvolts}$$

The coupling factor C was experimentally evaluated and the data indicated that the radio interference fields at the antenna are on the average almost the same as the RFI at the nearest power circuit.

CHAPTER VI
BIBLIOGRAPHY AND ABSTRACTS

RAILROADS AND TROLLEYS

1. L. J. Hibbard, F. T. Garry, G. N. Loomis, Multiple-Unit-Rectifier Motive Power-Induction Co-ordination Considerations on the New York, New Haven, and Hartford Railroad, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, pt. 2, Vol. 76, pp. 416-426, 1957.

2. E. W. Schumacher, New Methods for Eliminating Static Caused by Trolley and Electric Cars, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 23, No. 7, pp. 779-780, July 1935.

   Describes the use of a carbon sliding bow to minimize radio interference.

3. L. M. Howe, Radio Interference from Street Railway Systems, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 25, pp. 708-713, June 1937.

   Reports on study of RFI from the streetcar and from the overhead trolley system.

4. A. J. E. Funke, Resonant Shunts: Their Use for Elimination of Arc Rectifier Interference on the Electrified South African Railways, ELECTRICIAN, Vol. 121, pp. 91-94, July 22, 1938.

5. Suppression of Interference from Trolley Buses, British Electrical and Allied Industries Research Association, Rpt. M/T 29, 1934.

6. E. Restle, O. Schneider, Suppression of Interference in Radio Transmission Due to Electric Traction Systems, SIEMENS REVIEW, Vol. 12, No. 3, pp. 91-95, 1936.

7. S. Whitehead, L. Daniel, Trolley Buses -- Magnitude of Radio Frequency Disturbance from and the Use of Condensers and Other Devices in its Suppression, British Electrical and Allied Industries Research Association, Rpt. M/T 39, 1935.

8. S. Lemoine, Using Condensers for Eliminating Interference from Electrical Tramways, WIRELESS ENGINEER, Vol. 16, pp. 3-5, January 1939.

9. C. V. Aggers, W. E. Pakala, W. A. Stickel, Effect of Radio Frequencies of a Power System on Radio Receiving Systems, ELECTRICAL ENGINEERING TRANSACTIONS, Vol. 62, pp. 169-172, April 1943.

"This paper is concerned with high voltage apparatus and describes tests and methods for calculating the over-all effects on radio reception resulting from the radio-frequency voltages produced incidentally by power apparatus."

10. Reber, Eliminating Power Plant Radiation, TELE-TECH, Vol. 14, pp. 77+, May 1955.

"Causes of objectionable electromagnetic radiation from power plants are discussed and their causes are explained. Practical experiences with the operation of a diesel engine power plant at an altitude of 10,020 feet are described."

11. H. R. Klewe, Interference Between Power Systems and Telecommunication Lines, British Electrical and Allied Industries Research Association, Rpt. M/T 126, Published by E. Arrold, Ltd.

"Formulas are given for estimating the effects for different types of power lines and hints for practical calculations and examples. Chapter 3 covers power system characteristics and phenomena affecting telecommunication systems adversely; Chapter 4 deals with the effects in telecommunication circuits arising from interference peculiarities and sensitivity of these circuits; Chapter 5 discusses telephone interference by induction of audio frequencies."

12. A. Morris, Interference of Electrical Plant with the Reception of Radio Broadcasting, INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, JOURNAL, Vol. 74, pp. 245-263, 1934.

Briefly describes the sources of interference in an electrical plant and general methods of suppressing them. Appendix 2 categorizes the interfering equipment by type, and indicates the type (radiated and/or conducted) and range of the interference. Appendix 3 tabularizes the technical particulars of various suppression devices together with their specific application.

13. R. Ficcki, The Interference Problem Associated with

Power Systems and Communication Lines, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 025).

"The report shows that with a few simple facts that are generally available, one can determine what effect a power line would have on a nearby communication system. The technique demonstrated makes possible a quick approximation so that design criteria may be developed while the communication system is being installed."

14. Location of Radio Interference on Rural Power Systems, U. S. Rural Electrification Administration, Sept. 1950, (PB 103514).

15. C. M. Foust, C. W. Frick, Measurements Pertaining to Coordination of Radio Reception with Power Apparatus and Systems, ELECTRICAL ENGINEERING, Vol. 62, No. 6, pp. 284-291, June 1943.

"This paper gives the results of practical experience with standard equipments and methods for the measurement of radio influence factors. The various elements in the chain between measured characteristics of the power apparatus and the noise measured in the radio set are analyzed. Quantitative values for the various factors involved in average cases are given."

16. R. Moeher, Mutual Interference between Wired and Wireless Radio Services, ELEKTROTECHNISCHE ZEITSCHRIFT, Vol. 63, pp. 113-116, March 1942.

"Under normal telemetering conditions and power it was ascertained that the field strength at a 100 m. distance normal to the power line was a few mv/m; at 3 Km it was approximately 1 microvolt/meter which is below the noise level at these frequencies. The author states that the only cases of interference observed were at distances less than 500-600 meters."

17. V. B. Frost, E. F. H. Gould, Practical Aspects of Telephone Interference Arising from Power Systems, INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, JOURNAL, Vol. 93, pt. 1, pp. 255-67, June 1946.

"The paper summarizes investigations on telephone interference carried out in this country (England) between 1934 and 1944. The paper is divided into six sections: (1) Electromagnetic Induction at

Fundamental Frequency -- A comparison of calculated and measured values of induced voltage at various sites shows that in most cases good agreement is possible with the available data on earth resistivity; (2) Interference at Audio Frequencies -- Results of tests are given which show that noise interference is serious from faulty power lines which are maintained in operation through the use of arc suppression coils; (3) Multiple Earthing of High-Voltage Systems; (4) Multiple Earthing of Low-Voltage Systems -- Tests show that the interconnection of 1 v. systems, each grounded at one point is unlikely to cause interference; (5) Apparatus Developments -- Gas discharge tubes, noise-eliminating filters and an improved psophometer are described; (6) Rise of Earth Potential -- Records of damage sustained and the precautionary measures which can be taken are discussed."

18. F. Krug, Radio Interference Caused by Poorly Grounded Cable Sheath, ELECTRICAL WORLD, Vol. 87, pg. 718, 1926.

"Static interference caused by poor ground on lead cable sheath in city-wide HV distribution system."

19. S. Pierce, Radio Interference from High Voltage Distribution Systems, British Electrical and Allied Industries Research Association, Rpt. M/T 22, 1954.

20. Radio Interference with Utility Operations, ELECTRICAL WORLD, Vol. 145, pg. 26, April 23, 1956.

Briefly discusses the increased crowding in the power radio service with consequent interference with power utility radio operations.

21. M. Rathpletz, H. Williams, Rural Inductive Coordination Practices, ELECTRICAL ~~WORLD~~, Vol. ~~168~~, No. 2, pp. 148-150, Feb. 1949. ENGINEER 68

"This article covers the solution of many of the numerous inductive coordination problems involving rural power and communication circuits."

22. C. W. Frich, Short Cut Method of Estimating Telephone Influence Factors of Power Systems with Rectifier Load, ELECTRICAL ENGINEERING TRANSACTIONS, Vol. 63, pp. 91-96, March 1944.

"Herein is described a practical short-cut method of estimating power-system TIF at a rectifier supply point. It is based on previously demonstrated

methods of calculating harmonics produced by rectifiers together with certain simplifying assumptions as to the characteristics of rectifier and power circuits. The results are reasonably consistent with test data In a coordination study the TIF has to be considered in combination with other factors, such as the type and location of circuits."

23. Marshall, Telephonic and Radio Interference from Hi-Voltage Systems, ENGINEERING, Vol. 170, pg. 103, Aug. 4, 1950.

Cites various causes of telephonic and radio interference from high-voltage systems in England in 1949. The main causes of interference were surface leakage over insulators, faulty insulators or contacts in isolating switches, live joints, etc. Some interference was caused by defects in small transformers, mainly of the pole mounted type.

MISCELLANEOUS

24. Protection Ratios for Carrier Current Systems Operating in the Frequency Band 200-415 KC, Radio Tech Commission for Aeronautics. May 1951, (Paper 78-51/00-41), (ATI 131 118 (3-4)).

"A study of the effects of radio frequency signals radiated by carrier current systems upon the reception of signals from aeronautical aids operating in the 200-415 KC band is reported. A survey was sponsored to determine the radiated field intensity of represented carrier current systems. The nature and extent of interference to navigation aids will depend on the characteristics of the carrier radiation and the susceptibility of the radio navigation and communication to interference. It is recommended that within the 200-415 KC band, continued use of carrier current systems which radiate signals having field strength of less than 10 microvolts/meter at a distance of 500 ft. from the line not be restricted."

25. R. Burgholz, Radio Interference Occurring in the Underground Working of Coal Mines, WIRELESS ENGINEER, Vol. 22, pg. 244, May 1945.

"The interference measurements carried out by the writer in mines lead to the conclusion that a line-guided h.f. transmission below ground is practicable. If an interference voltage up to 1000 microvolts is taken as permissible on the line, only in

a limited number of cases need interference-quenching measures be taken, provided that sections with overhead-supply lines for the mine-railway locomotives are avoided. In such sections the use of screened cable would be essential for satisfactory transmission."

CHAPTER VII

INDUSTRIAL EQUIPMENT INTERFERENCE

GENERAL

Changes in the electrical conditions of a circuit will generate components of current and voltage at various frequencies. The more rapid the change, the higher the frequency components will extend. Since all classes of electrical equipment will cause fluctuations in current and voltage they are, therefore, potential sources of radio interference. Gill and Whitehead, in ref. (3), have identified many of these sources of interference, both radiated and conducted. For instance in an electric trolley-bus the collectors, the main contactors supplying and controlling the motor, and the driving motor all radiate interference. The operating coils of the contactors and switches of the driving motor of an electric elevator are sources of interference. Mercury arc rectifiers cause continuously distributed interference over the broadcast bands. Bellaschi and Aggers, in ref. (7), point out that most electrical equipment operates in either air or oil. Therefore the corona characteristics of these two dielectrics either alone or in combination are important factors in radio interference. Radio interference measurements in both oil and air indicate that radio noise influence of electrical apparatus is primarily concerned with the apparatus or its parts in air.

HIGH FREQUENCY ARC WELDERS

High-frequency stabilized electric arc welders are used in the fabrication of such metals as aluminum. Frick indicates in ref. (15) that RFI from welding operations can take three different forms. It can be a single frequency from a vacuum tube oscillator; a band of frequencies from a spark oscillator; or broadband disturbances commonly known as radio noise. The interference can be minimized by using a shielded transformer, power line filters, oscillator shielding and proper HF output filtering. Murray suggests, in ref. (8), a method of reducing RFI by introducing a comparatively weak spark at the proper instant in each a-c cycle thereby minimizing the need for a continuous HF arc. By introducing the spark at the point of current zero pause the surplus sparks can be omitted and thereby keep the signal well below the RFI level. Measurement of the radiated and conducted energy from welders presents many changing conditions. Stehle has listed a number of them in ref. (9). Such factors as length and position of welding leads, operator position, power line position, electrode length and type, spark gap cleanliness and adjustment are just a few of the variables that lead to changes in field intensity measurements. Accurate results require that these conditions be fixed or isolated during interference measurements.

RADIO FREQUENCY HEATING EQUIPMENT

RF heaters are basically RF generators that produce

heat in an object during the manufacturing process. The operation is quite similar to the medical diathermy machine for inducing heat in the human body. Power input varies from a few hundred watts to as high as 50 kw. A vacuum tube oscillator usually serves as the source of energy. These oscillators generate a fundamental frequency plus a number of harmonics. Industrial heating can be broken into two categories: (1) Induction heating, i.e., heating of metals at frequencies below 500 kc: and (2) Dielectric heating, i.e., heating of non-conductors at frequencies above 2 mc. Rudd describes, in ref. (23), tests that indicate that dielectric heating equipment is the principal offender as far as RFI is concerned. The radiated energy from the induction heater operating at relatively low frequencies attenuates rapidly with distance. Radiation from dielectric heaters on the other hand will be detected at considerably greater distances unless properly shielded. Klingaman indicates in ref. (32) that the most practical method of locating sources of radiation is with a radio-frequency current probe. Possible paths of stray currents that will result in radiation from a typical installation are shown in Fig. VII - 1.

Currents I_1 and I_2 result from excess leakage through the faces of the screen or cabinet. I_3 is caused by the large opening in the otherwise shielded cabinet. I_6 results from leakage from faulty contacts about the door. I_7 is caused by the slit in generator cabinet. Currents I_4, I_5,

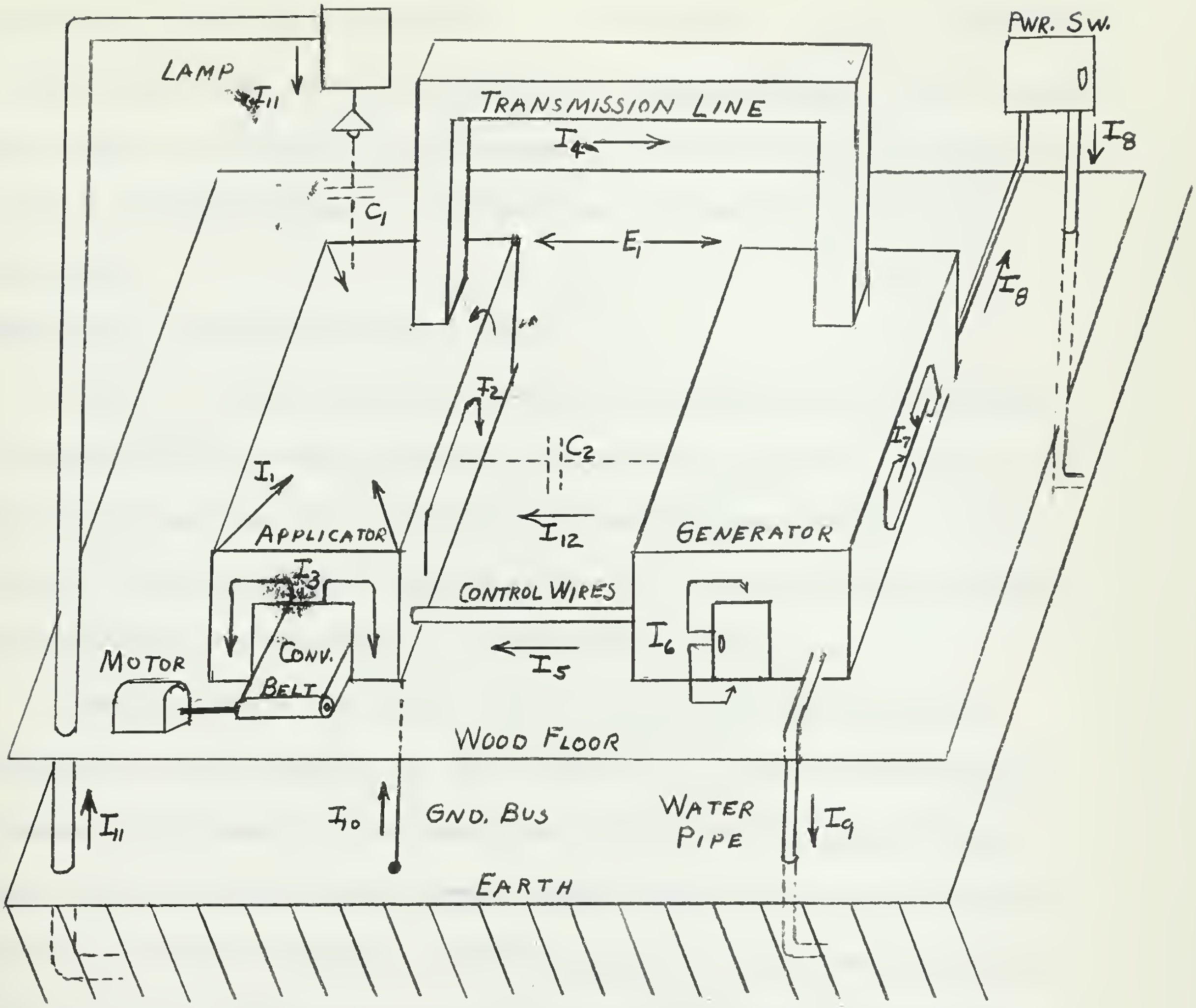

Fig. VII - 1 Stray Currents Result in Radiation from an RF Heater Installation

I_8, and I_{11} could be induced in the conduit exteriors by r-f leakage as is the case of I_9. I_{10} can occur if the ground bus has sufficient radiation resistance and may actually cause interference rather than reduce it.

The magnitude of the radiation is measured with a field intensity meter. Generally speaking, shields and filters provide the best means of minimizing interference from RF

heaters. Shields should be continuous without gaps, poor joints or unshielded openings. The shield should be made of a good conductor such as copper or bronze screen. The apparatus must be completely shielded either by its own cabinet or by a shielded room. Filters are installed in the line circuits.

ELECTRICAL MOTORS AND GENERATORS

There are two general methods for reducing the amount of interference generated by electrical machines. One is to reduce the amount of generated interference through proper design techniques and the other is to suppress the remaining interference that cannot be handled by design.

Motter states in ref. (39) that one of the primary causes of interference in d-c motors is in the commutation process. Voltage transients are set up each time an armature coil is commutated even though there may be no visible sparking at the brushes. Another source of interference in motors is the "surface noise" generated when a commutator or slip ring slips by a brush. Some of the factors affecting the intensity of this type of interference are magnitude of the current through the brush, brush composition, brush pressure, and commutator speed.

If design cannot bring the interference within tolerable levels then the engineer must resort to suppression and shielding.

Seaman points out in ref. (45) that commutation itself

is a function of several factors which must be considered in interference-free design.

> Factors which affect commutation most noticeably are: 1. A voltage drop in the coil being commutated which tends to prevent a uniform current density at the brush; 2. A rotational e.m.f. caused by the moving coil cutting the pole tip flux if the brushes are shifted. The direction of this e.m.f. should be such as to aid the reversal of current, which is advantageous to commutation; 3. A rotational e.m.f. caused by the moving coil cutting the cross-magnetizing flux. The direction of this e.m.f. is such as to oppose a reversal of current; 4. Changing current in the coil produces a change in flux linkages which induces an e.m.f. in opposition to the current changes of commutation; 5. Current changes in adjacent coils, undergoing commutation at the same time, will effect the flux linkages around the given coil, thus producing an e.m.f. of mutual induction. This e.m.f. of mutual induction will oppose the current change in the coil under consideration; 6. A voltage drop between brush and commutator due to contact resistance; 7. A voltage drop in the brushes due to brush resistance.

Usually the voltage drops due to coil resistance and brush resistance are very small and are quite frequently neglected. This does not necessarily mean that they do not affect radio interference generation, however. The factors which most noticeably affect commutation are the induced voltages due to self and mutual induction (called resistance voltage), induced voltage due to rotation in the pole tip flux (called commutating e.m.f.), and the contact resistance drop. The commutating e.m.f. aids the reversal of current and if it could be made equal to the reactance voltage, which opposes the reversal of current, excellent commutation would result.

Increased voltage drops due to the brush and brush contact resistance decrease the circulating current, but they also hinder the efficiency of the machine.

As was previously pointed out, interference is not entirely minimized by eliminating the visible sparking although it is greatly reduced. A reason why interference is still present with the elimination of the visible sparking is that there still may be voltage transients present due to non-linear current reversal during commutation.

A Burroughs Corporation report, ref. (44), further defines the following design principles:

> The voltages which are induced into the commutated coil from the field by transformer action should be minimized. This voltage can be minimized by keeping the turns ratio low and by making the self inductance of the coil low. Observing these general conditions will limit the amount of circulatory currents and thus reduce the inherent interference. When speed regulation is not too critical, use governors which respond less frequently. The fewer number of times the current is interrupted, the less interference will be generated. Chatter and bounce of brush and contacts should be eliminated. Maintain the motor and contacts at as cool a temperature as possible to minimize ionization between brush and commutator segments, governor contacts and switch contacts.

Moore describes, in ref. (43), various methods of suppression and shielding. Reduction of conducted interference is accomplished by the insertion of PI section filters in the power input lines. All external components should be enclosed within solidly constructed, well mated and rigidly secured metal cases, with proper allowance for ventilation. All interconnecting conductors and cables should be enclosed

in either rigid or flexible seamless conduit. A grounding contact should be installed so as to make secure and positive contact with the drive shaft at all times.

ELECTRICAL CONTACTS, SLIP RING, BUSHINGS AND BEARINGS INTERFERENCE

In evaluating radio interference generated by electrical contacts a knowledge of the gap phenomena is necessary. Stannard and Krackhardt state, in ref. (65) that:

> Appreciable spontaneous conduction may occur across the gap by mechanisms which are directly related to the strength of the electric field between the electrodes and which do not directly involve the nature of the atmosphere between the contacts. Once the gap has broken down, a variety of subsequent events may occur. After once being established, a conducting bridge may continue to exist with a durability that is related to the choice of contact material provided the current flow which results is sufficiently small and the contacts are not in relative motion. Usually the circuit conditions are such as to cause this bridge to explode with the possibility that the resulting hot spot at the negative electrode may serve to provide electrons for a low-voltage arc discharge. This discharge may become permanent if the resulting current flow is sufficient to maintain the required cathode temperature or transient if not. A consideration of the two types of noise-producing breakdowns occurring at the gap indicates the requirements which must be fulfilled if the radio noise is to be minimized at its source. Overshoots of the gap voltage may be effectively reduced and the noise caused by high voltage discharges eliminated through the proper use of non-linear resistances which present a much lower value to the abnormal voltages, using, for example, dry-disc rectifiers. Such devices, however, are not effective in significantly reducing the voltage-gradient type of breakdown that may occur at voltages less than the supply value. In this case, some means must be found for maintaining a near-zero voltage across the contact gap during the initial stages of switch opening and the final stages of switch closing.

A recommended technique is a capacitor in series with a dry-disc rectifier thereby shunting the initial voltage transient with a relatively slow discharge time when the switch is closed. The effects of suppression devices must also be considered with respect to other than contacts alone because they may cause an increase in radio interference rather than decreasing it.

In analyzing the noise generated by slip rings, Radnick, in ref. (69), states that there are three different types of noise present. The first type, the so-called self generated noise, is independent of current and voltage. It is probably caused by thermal e.m.f. resulting from momentary hot spots. The second type of noise is caused by variations in contact resistance and is directly proportional to the current. It is theorized that this type of noise is caused by the breakdown in a semi-conducting film. The third type of noise was caused by uneveness in the slip ring resulting in the separating of the brush and slip ring, i.e., brush bounce. Forster, in ref. (70), indicates that this results in a square wave voltage of constant height but variable width. Of the three types of noise the one associated with loss of contact creates the most interference at high slip ring speeds. In order to suppress this interference brushes have been made of molybdenum wool which absorbs the shock of the bounce and takes the shape of the slip ring. Silver has been used to form the slip ring so that films formed would

be easily removed by the brush. Also the molybdenum-silver combination produced low thermoelectric voltages.

The noise generated by anti-friction bearings is discussed by Dinger and Raudenbush in ref. (63). Their tests indicated that the radio interference was generated by sharp pulses of current flowing between the balls and the races. This can be caused by the lubricant film breaking down, or momentary metal to metal contact between the bearing and the race, or both. It was determined that a low viscosity lubricant was the most effective type of lubricant to use in radio noise reduction.

CHAPTER VII
BIBLIOGRAPHY AND ABSTRACTS

GENERAL

1. A. P. Hale, Electrical Interference, Haywood and Co. Publishers, 1956.

   "The wide range of higher-frequency 'man-made' noise, normally the result of operating electrical machinery, is discussed in this book. Chapters are devoted to causes, effect, aerial systems, measurements, location, avoidance and filters. A list of British Standards is included in the bibliography."

2. D. Weaver, Electrical Interference Problems, Stanford Research Institute, Calif., Interim Rpt. No. 2, Stanford Research Institute Project No. 336.

3. J. Gill, S. Whitehead, Electrical Interference with Radio Reception, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 83, pp. 345-394, July-Dec. 1938.

   "The paper describes the method of assessment of the interference to radio reception from electrical equipment, and determines the level to which such interference must be reduced to permit satisfactory service. The methods of achieving this result are described for the various classes of interfering equipment."

4. E. Davis, Electronics Interference Reduction Aboard Naval Vessels, Proceedings of 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 375-390, Feb. 1957, (AD-234 211).

   "This paper describes the interference reduction procedures, methods and techniques used by the Long Beach Naval Shipyard in locating, identifying, isolating and correcting shipboard interference reduction deficiencies. It contains a description of the conduct of an actual electronics interference survey on a Navy Ship at sea and lists the electronic equipment used."

5. Interference Problems Arising from Industrial Electronic and Electro-Medical Apparatus, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 94, pt. 3, pp. 57-58, Jan. 1947.

   "In reference to industrial heaters, many substances

when heated change their electrical properties, and owing to this it is found that many oscillations vary in frequency and power output during the heating cycles. Recommendations for dealing with the interference are also advanced."

6. Investigation of Radio Noise Generation in Aircraft Electrical Machinery, General Electric Co., July 1950, (ATI 80493 (3-4)).

   "Factors affecting the generation of r-f voltages in aircraft electrical machinery were investigated. Information was compiled applicable to the design of aircraft rotating electrical machinery which would minimize r-f voltages or noise and which would materially simplify source filtering of electrical equipment. Sample developmental brushes were designed to reduce generation of radio noise and it was found that 90% of radio noise from common d.c. machines is directly attributable to the sliding brush contact. Other factors considered as effective means of reduction of noise were a stabilized brush feed, brush lamination, normal oxide layer in the commutation film, chromium surfaces, influence of chromium resistivity, multiple metal to metal contacts, and practical filter application."

7. Bellaschi and Aggers, Radio Influence Characteristics of Electrical Apparatus, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 57, pp. 626-633; ELECTRICAL ENGINEERING, Vol. 57, pp. 626-233, Nov. 1938.

   "Radio frequency influence factors vary in character, depending on the electrode insulation arrangement of the source, and also the dielectric medium. Humidity and relative density of the air affect the radio-influence factor and accordingly certain correction factors for atmospheric conditions need be recognized. The radio influence factor characteristics of insulation in air and oil, reported in the paper, establish normally only apparatus in air need be considered for the effect of radio noise influence, as in coordinated apparatus design the strength of parts in oil will exceed those in air."

ARC WELDERS

8. J. G. Murray, Current-Rectification and High Frequency Interference in Inert Gas Welding, WELDING JOURNAL, Vol. 33, pp. 561-563, Jan. 1954.

Discusses the need for a high frequency spark to start the arc and sustain it. Concludes that a comparatively weak spark introduced at the proper time in each ac cycle will give good consistent inert arc welding over the entire range of the transformer without RFI.

9. F. N. Stehle, HF stabilized Electric Arc Welders--Measurement of Radiated and Conducted Energy, U. S. BUREAU OF SHIPS JOURNAL, Vol. 6, No. 10, pg. 27, Feb. 1958.

Lists the many problems and varying conditions faced when measuring radiation and conducted energy from welders. Proposes improved methods of measuring interference.

10. F. N. Stehle, R. I. Branch, Interference Studies on an R. F. Stabilized 60-Ampere AC Inert Arc Welder Submitted by General Electric Company, York, Penna., Naval Engineering Experiment Station, Annapolis, Md., Letter Rpt. 28, Rpt. No. 810086, May 1957, (AD 141 266).

"A reduced duty-cycle HF-stabilized inert-gas electric arc welder was subjected to interference studies. Tests indicated that the welder does not conform to proposed FCC minimum requirements. Modifications to provide more nearly interference-free operation include improvement of the shielding for the oscillator, welder case, and torch leads; replacement of the spark-gap oscillator with a crystal controlled vacuum-tube oscillator and suitable buffer circuits; the installing of a bandpass filter in the oscillator output circuit for the elimination of harmonics that might be generated by the crystal-controlled oscillator; and design of the crystal-controlled oscillator and its associated circuits so that the RF output will remain within FCC limits for this type of equipment. It is recommended that the welder circuitry be redesigned to use HF energy only for starting purposes."

11. F. N. Stehle, Measurement of Radiated and Conducted Energy from High-Frequency Stabilized Electric Arc Welders, Proceedings of 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 397-404, Feb. 1957, (AD-234 211).

12. New System Eliminates Radio Interference with Inert Arc Welding, POWER GENERATION AND POWER PLANT ENGINEERING, Vol. 53, pp. 87-88, Feb. 1949.

"Many old welding equipments used an RF voltage to

maintain the welding arc which caused serious interference if not shielded properly. The GE balanced wave welder eliminates the use of RF and its resultant interference by using a bank of capacitors to completely balance the a.c. circuit."

13. On the Interference with Radio Reception Caused by High-Frequency Welding and Methods for its Suppression, WIRELESS ENGINEER, Vol. 21, No. 38, Jan. 1944, Abstract from Russian.

"Tests were carried out to measure the interference produced by a spark oscillator of Russian manufacture. The following methods were determined to be effective in eliminating RFI. (1) the feeding of the oscillator through a screened transformer (2) protection by filters of the supply mains feeding the welding transformer (3) use of an h.f. choke at the output of the oscillator to suppress frequencies above that to which the oscillator is tuned (4) screening of the leads and of certain components of the circuit."

14. R. R. Lobasco, Problems of Radio Interference, WELDING ENGINEER, Vol. 34, No. 2, pp. 33-38, Feb. 1949.

"The manual on high frequency stabilized inert-gas welding published by a NEMA committee is discussed. It is pointed out that short leads, special grounds, and shielding of exposed wires are necessary steps."

15. C. W. Frick, Radio Interference Problems in Welding, ELECTRICAL ENGINEER, Vol. 68, pg. 165, Feb. 1949.

Describes the factors involved in interference from arc welding and briefly discusses how the interference is generated.

16. Scott L. Shive, Radio Interference Suppression of High Frequency Arc Welder, Coles Signal Lab., Rpt. T-1219, May 1949, (PB 97469).

"Report covers investigation to determine measures necessary to provide effective R-I suppression for the high frequency stabilized arc welding unit Model TH-300."

RF HEATING EQUIPMENT

17. Abatement of Radio Interference from Electro-Medical and Industrial Radio Frequency Equipment, British Standards Code of Practice CP 1002:1947, British Standards Institute (London, England), 1947.

18. P. S. Rand, Curing Industrial TV; Preventing Radiation from R.F. Heating Machines, QST, Vol. 35, pp. 29-33, Sept. 1951.

"The article describes an actual case of interference and how it was cured. Shielding and filtering techniques are discussed and illustrated. The offending dielectric heater was completely shielded utilizing the equipment cabinet and copper screening. An AC line filter was used in the supply circuit."

19. P. S. Rand, J. J. Lamb, A. J. Riley, Curing RF Heater TV Interference, MODERN PLASTICS, Vol. 29, No. 1, pp. 101-102+, Sept. 1951.

"Describes the sources of RFI from industrial heaters and gives detailed methods of reducing the interference by means of shielding, filtering, and shielded rooms."

20. E. R. Bell, M. E. Dunlap, Elimination of Standing Waves on Electrodes for High Frequency Dielectric, Central Air Documents Office.

21. P. S. Rand, J. J. Lamb, A. J. Riley, Eliminating Radio Interference from Radio-Frequency Power Equipment, ELECTRICAL MANUFACTURING, Vol. 48, No. 4, pp. 138-142+, Oct. 1951.

22. F. E. Ilgekit, K. W. Bajenow, Essential Principles for the Protection of Radio Reception Against Interference Produced by High Frequency Induction Heated Tube Generators, RADIOTECHNIQUE, Vol. 4, No. 6, pp. 14-23, 1949, Translated by L. C. Stevens, June 1952, (PB 107394).

23. W. C. Rudd, High Frequency Heating in the Radio Spectrum, ELECTRICAL ENGINEERING, Vol. 66, pp. 570-576, June 1947.

Discusses induction and dielectric heating for manufacturing processes. Test results for shielded and unshielded units are shown. The history of the regulations concerning industrial heaters is also outlined.

24. Interference from Industrial Electronic Apparatus, WIRELESS WORLD, Vol. 52, No. 6, pg. 198, June 1946.

25. J. Miedzinski, S. F. Pearce, Interference from Industrial R. F. Equipment -- Performance of Screening Rooms, British Electrical and Allied Industries Research Association, Rpt. M/T 104, 1949.

26. George H. Brown, Measurement of Interference from Radio Frequency Heating Equipment, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 67, pt. 2, pp. 1102-1106, 1948.

The paper describes some of the measurements of the fields from typical equipment and discusses some of the pertinent factors which should be considered in connection with these measurements. The transition of the analysis from the high frequency solution to the frequencies of interest in induction heating is made by means of van der Pol's solution of the wave equation. The near fields of radiating loop are established and correlated with measurements. Estimates of radiated power from typical industrial oscillators are made.

27. Eugene Mittleman, The Problem of Constant Frequency in Industrial High Frequency Heating Generators. Proceedings of the 1946 National Electronics Conference.

28. L. L. Langton, Radio Heating Equipment, IV, Interference Problems, Importance of Efficient Screening, WIRELESS WORLD, Vol. 50, pp. 212-213, July 1944.

29. Radio Heaters Threaten Air Navigation Safety, SCIENCE NEWS LETTER, Vol. 77, pg. 166, March 12, 1960.

30. A. Turney, Radio Interference from Industrial R.F. Heating Equipment, ELECTRONIC ENGINEERING, Vol. 19, No. 234, pp. 251-2554, British Electrical and Allied Industries Research Association, Rpt. M/T 88, Aug. 1947.

31. Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, New York, 14 pp., May 1950.

32. G. W. Klingaman, Reduction of Interference from High-Frequency Heating Equipment, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 68, pt. 1, pp. 718-724, 1949.

"The nature of the radiation and possible paths that will cause radiation from an installation are described. Remedial methods by means of physical isolation, cancellation of equal and opposite fields in adjacent conductors, shielding and filtering are discussed. Good design practices are also outlined."

33. R. A. Whiteman. Shielding Industrial Electronic Generators, RADIO-ELECTRONIC ENGINEERING, pp. 8-104, Sept. 1947.

"The industrial electronic generator consists essentially of three sections or components, each capable of radiating interfering electro-magnetic waves. These parts are the radio frequency oscillator, the load circuit and the transmission line between them. The basic equations for determining shielding effectiveness are derived and are related to the problem of radiation from the r-f heaters."

34. G. W. Klingaman, G. H. Williams, Shielding of Dielectric Heating Installations, ELECTRONICS, Vol. 18, pp. 106-109, May 1945.

"Field intensity measurements in the vicinity of a 9-Mc electronic generator show effects of various shields, grounding arrangements and line filters on radiation when feeding 6 KW into a dummy load. An oscillating wavemeter locates points of radiation leakage."

35. A. Turner, Summary of Interference from Industrial R. F. Heating Equipment, WIRELESS WORLD, Vol. 53, pg. 326, Sept. 1947.

36. Survey of High Frequency Heating, Bureau of Ships Contract 34227, Task Order 2, Raymond W. Wilmotte, Inc., June 1947.

37. O. Noeske, What to Do About Certifying Your Induction Heater, AMERICAN MACHINIST, Vol. 97, pp. 144-146, March 16, 1953.

MOTORS

38. W. O. Ordinanz, Analysis of Motor Noise and How It Can Be Minimized, PRODUCT ENGINEERING, Vol. 18, No. 12, pp. 110-115, Dec. 1947.

39. D. P. Motter, Commutation of D-C Machines and Its Effects on Radio Influence Voltage Generation, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 68, pt. 1, pp. 491-496, 1949.

"1. One of the main causes of radio influence voltage generation in d-c rotating machinery is transient voltages produced during commutation.
2. The magnitude of the transients and of the radio influence voltage generated is dependent upon linearity of armature coil current reversal.
3. Black band commutation is no assurance of the best quality of commutation to minimize radio

influence voltage generation.
4. Where interpoles are not employed, there is a finite armature current at which commutation is of better quality and minimum radio influence voltage is generated while using standard brushes.
5. Developmental laminated brushes can improve linearity of armature coil current reversal and provide an appreciable reduction of radio influence voltage generation over a wide range of armature currents."

40. D. P. Motter, Control of Radio Influence Voltage in Rotating DC Electrical Machines, Proceedings of Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD 76686).

"Two major aspects in the control of Radio Influence Voltage in rotating d-c machines are: 1. Reducing the generation of R.I.V.; 2. Suppressing the generated R.I.V. that cannot be reduced through practical machine design. Voltage transients which are of the repetitive type are mainly caused by commutation of the armature coil and may be reduced by improved commutation. Another type of voltage transient which occurs is the non-repetitive type or 'surface noise' produced when the commutator or slip ring surface slides across the face of the brush. This type of 'surface noise' has many causes which have been investigated and improved. Examples are brush material, commutator bar material, pressure of brushes on the commutator and several others."

41. Edward Binek, Sylvester F. Pelowski and others, Fractional-Horsepower D.C. Motors RF Minimization, Radio Interference Lab., Burroughs Corp., Oct. 1954, (AD 45812).

42. Installation of Radio Noise Filters in Heater and Anti-Icer Motors -- P-61A, U. S. Army Air Forces, Apr. 1945, Tech. Order 01-15FB-29, (PB 41878).

43. W. Moore, Interference Investigations of Electronic Variable Speed Drive, American Industrial Devices, Dec. 1954, (AD 58634).

"This report covers investigation of interference produced from Electronic Variable Speed Control Drives as used in commercial developing and reproduction equipments, similar to those supplied to the Navy Department. Of particular interest may be found the application of Thyratron tubes for speed control purposes. Research and development

work relative to the location of interference sources and design of appropriate corrective measures to provide conformance with Bureau of Ships Navy Department specification MIL-I-16910A are likewise detailed in this report."

44. Motors that Meet MIL-E-16400 (Ships) and MIL-I-16910A (Ships), Burroughs Corp., May 1955, (AD 85120).

"This report contains detailed and general considerations for the design, construction and testing of several universal fractional-horsepower motors that meet the applicable requirements of Military Specifications MIL-E-16400 (SHIPS) and MIL-I-16910A (SHIPS). Some of the methods and techniques used to reduce the inherent interference of fractional-horsepower direct-current rotating machinery were applied to these universal motors. The principles of interference reduction used here can be applied to any universal motor design."

45. Floyd D. Seaman. Radio Interference Minimization Design Techniques -- Fractional Horsepower D.C. Motors, Burroughs Corp., Jan. 1954, (AD 35286).

"This report consists of techniques used in designing fractional horsepower direct-current motors to minimize radio interference. An attempt to correlate the minimization of radio interference techniques to existing design practices is made. Design factors considered are: (1) various formations for armature windings: (2) threaded commutators; (3) brush resistance and composition; (4) load requirements and their effect on armature reaction. Other pertinent factors considered are: (1) effects of load on series and shunt type motors; (2) effect of altitude; (3) methods of filtering."

46. S. I. Philpott, Radio Interference Suppression, ELECTRICIAN, Vol. 144, pp. 1025-1029, March 1950.

"An expert on fractional horsepower motors, Mr. Philpott deals mainly with interference caused by such motors, but much of the information will be found of general application."

47. S. Majumdar, S. Khastigir, S. Sen, Studies of Electrical Interference to Radio Reception, INDIAN JOURNAL OF PHYSICS, Vol. 17, pp. 271-282, Oct. 1943: WIRELESS ENGINEER, Vol. 21, pp. 538-539 (Abstract), Nov. 1944.

"The electrical interference in the frequency

ranges 0.65-1.5, 3-6, and 7-20 Mc from d.c. electric fans and motors was studied. Four different studies were made: 1) measurement of the RF radiation field, 2) determination of the resonant frequency of armature coils, 3) measurement of the horizontal to vertical ratio of field strengths, and 4) oscillographic studies of the noise components."

48. S. Khastigir, S. Sen, Suppression of Radio Interference from Electric Motors, CURRENT SCIENCE, Bangalore, Vol. 12, No. 5, pp. 146-147, May 1943.

GENERATORS

49. A. M. Brown, Brushless, Regulated Generator of Radio-Interference-Free Design, Proceedings of 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 330-339, Feb. 1957, (AD-234 211).

"This paper describes a generator of radio-interference-free design which produces a conventional voltage regulated output without requiring slip rings or commutator. There are no sliding or arcing contacts to initiate radio interference. The unique feature developed is the manner in which regulated excitation is supplied to the rotating field."

50. J. W. Teegarden, Combination Starter-Generator for Jet Engines, Air Material Command, May 1949, (ATI 69225 (3-4)).

"A number of modifications attacking the starter-generator interference problem at the source are listed, as well as re-routing of the canopy wiring and the incorporation of a standard 10-amp radio interference filter in the engine ignition junction box. The filter is to be inserted in series with the starter-generator field."

51. A. Mason Brown, Development of a Brushless Regulated AC Generator of Radio-Interference-Free Design, Naval Civil Engineering Lab., Port Hueneme, Calif., Final Report, Technical Rpt. No. 032, (AD-209 529).

"Power generators were studied with the object of reducing radio interference. Study revealed that brush sparking at the commutator and slip rings of ac power generators and associated exciters was a source of severe radio interference and that brush, commutator and slip-ring wear were the main sources of all generator troubles and maintenance expense.

The development is described of a generator of radio-interference free design which produces a conventional voltage-regulated output without requiring brushes, commutator, or slip rings. There are no sliding or arcing contacts to initiate radio interference. The unique feature developed is the manner in which regulated excitation is supplied to the rotating field. Acceptance tests showed that the generator complied with Navy voltage regulation specifications. Tests showed that it was radio-interference-free to MIL-I-16910 standards. Total running time to date logged on the generator is 1600 hr. It is concluded that brushless generators with standard performance characteristics can be built with all sliding, current-carrying surfaces eliminated. Such machines have inherent in their design prospects for a degree of highly reliable operation unattainable in conventional generators."

52. Leonard W. Thomas, Procurement Scheduled for Radio Interference-Free Power Equipment, U.S. BUREAU OF SHIPS JOURNAL, Vol. 3, No. 3, pp. 29-34, July 1954.

Describes the Navy Model CXRB Gasoline Generator Set which delivers 600 watt, 115 volt, 60 cycle, single phase a.c. output. It has been designed to cause a minimum of radio interference. Radiated interference at ten feet was 10 microvolts at 14 kc to 150 kc, and 5 microvolts at 15 kc to 25 kc. Conducted interference values did not exceed the following:

60 kc to 300 kc	--	10 microvolts
301 kc to 25 mc	--	5 microvolts
26 mc to 400 mc	--	20 microvolts.

53. John L. Pancoast, Radio Interference Studies of an AN/SPN-11 Radar Power Supply for 24-Volt DC Power Source, Manufactured by Electric Specialty Company, Stamford, Connecticut, Letter Report, Naval Engineering Experiment Station, Annapolis, Md., EES Rpt. No. 810034-G, 15 Oct. 1957, (AD-208 746L).

54. E. S. Van Valkenburg, E. A. White, Radio Interference Studies of Aircraft Generators, Naval Research Lab., E-2807, April 1946, (PB 123 368).

55. Bruce Jackson, Radio Noise Test on General Electric Tachometer Commutator, U. S. Army Air Forces Experimental Section, Exp. M-54-656-477 G, 1942, (PB 10162).

"Report on noise level test of tachometer commutator, General Electric commutator assembly Type TJ-21,

and recommendation for changes necessary to lower the level. Graph."

56. A. Brown, Regulated Radio-Interference-Free Generators, ELECTRONIC DESIGN, pp. 136-139, 15 July 1957.

"A radio-interference-free generator design which produces a conventional voltage regulated output without requiring brushes, slip rings or commutators is described. There are no sliding or arcing contacts to initiate radio interference. The most unique feature of this generator is the manner in which excitation is supplied to the rotating field. Regulation is obtained by means of a static type voltage regulator."

57. Suppression of Interference from Large DC Generators, Air Services Telecommunication Division, Dept. of Transport, Canada, Circ. S11-10-40, May 1951.

58. Suppression of Radio Interference Created by Engine Generator Units, U. S. Army Signal Corps, Manual SIG-461-1, August 1945.

59. G. L. Oscarson, I. C. Benson, Telephone Influence Factor in Synchronous Machines, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 70, pt. 1, pp. 743-748, 1951.

"In commercial generators, distortion in the voltage wave may be caused by (1) variation in the speed (2) non-uniform or pulsating magnetic fields; or (3) distribution and connection of the armature conductor. The electric load on the generator may change the TIF. The no-load TIF may be reduced from 20 to 50% by applying full load, if balanced on all phases. The magnitude of the load current affects the magnetic saturation within the generator and thereby also affects the TIF. The power factor of the load which relates the load current to its voltage and in turn the motor position with respect to the stator, will affect TIF. Generally, unity power factor loads, or even lagging power factor loads, will result in a lower TIF than on leading power factor loads. Manufacturing factors affecting TIF are also discussed."

RECTIFIERS

60. D. W. R. Cobbe, Interference from Cathodic Protection Rectifiers. POST OFFICE ELECTRICAL ENGINEERS JOURNAL, London, Vol. 45, pp. 68-71, July 1952.

"Outlines an investigation carried out in the Middle East to determine what interference to telecommunication circuits would result from applying rectifier-operated cathodic protection to oil pipe lines. The nature of the interference is considered and a brief description given of the test procedure and test observations. Precautions for limiting such interference to a satisfactory level are indicated."

61. Interference from Mercury Arc Rectifiers and Effect of Filter Circuits, British Electrical and Allied Industries Research Association, Rpt. M/T 13, 1932.

62. W. Nethercot, Radio-Frequency Disturbance from Mercury-Arc Rectifiers and its Suppression, British Electrical and Allied Industries Research Association, Rpt. M/T 48, 1937.

SHAFT, BEARING, SLIP RINGS, ELECTRICAL CONTACTS

63. H. E. Dinger, J. E. Raudenbush, Anti Friction Bearings As a Radio Noise Source, Naval Research Lab., 4023, July 1952, (ATI 159885 (3-4)).

"It was found that noise generation was the result of erratic pulses of current flowing between the races of the bearing as a result of dielectric breakdown of the lubricant film and/or momentary metal to metal contacts between the balls and races. The potential causing this current flow in actual machines would exist between the shaft and the frame by electric induction as a result of the strong electric fields normally present. Any leakage currents tending to flow across the bearing as a consequence of inefficient insulation of the windings would also be a possible cause of radio noise. Anti friction bearings lubricated with low-viscosity lubricants, because of their much lower shaft to frame resistance characteristics were found to generate somewhat less radio noise than when lubricated with high viscosity lubricants."

64. L. Germer, T. Smith, Arcing at Electrical Contacts on Closure--Part III--Development of an Arc, JOURNAL OF APPLIED PHYSICS, Vol. 23, No. 5, pp. 553-562, May 1952.

"A description is given of a system made up of experimental electrodes and an oscilloscope by means of which the potential across the electrodes can be recorded. As an arc starts the potential across the electrodes decreases more or less gradually

from the applied voltage to a steady value characteristic of the metal of the electrodes. The course of this change is extremely variable as is also the time over which the change is spread. The average value of the time appears to vary with circuit inductance and with the nature of the electrode surfaces."

65. G. Stannard, R. Krackhardt, Contact Noise and Problem of the Suppression, Proceedings of Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD 76686).

"The special distribution from 15 KC to 20 Mc of radio noise that results from the operation of current-interrupting contacts in dc circuits having supply voltages of 48 volts or less and steady state currents of 0.5 ampere or less has been correlated to some degree with the values of the circuit parameters and with the nature of the breakdown phenomena occurring in the contact gap during opening and closing of the switch. Radio noise is caused by two broad classifications of gap breakdown: one related to the voltage across the gap and the other dependent on the voltage gradient within the gap. The former may be eliminated by the use of nonlinear resistances or rectifiers, but such suppressors have not been found to be effective in reducing the second type of breakdown."

66. T. Hammell, M. Kichring, Electrical Noise Level Measurements of NRC Mercury Sliprings Rotating at 12000 RPM and Surface Rubbing Speed of 70 ft./sec., National Research Council of Canada, July 1961, (AD-260 006).

67. Billy M. Horton, Electrical Noises Generated in Sliding Contacts, Naval Research Lab., Rpt. 3408, Jan. 1949.

"An investigation has been made of various materials and methods for transmitting electroencephalograph signals through a rotating joint. It is found that low friction with smooth sliding, freedom from corrosion films, multiplicity of contacts, and similarities in thermoelectric properties of the materials in contact are all desireable characteristics. Effects of variations in speed, number of contacts, and normal force are investigated. Several novel sliding contact arrangements are tried. Measurements of generated electrical noise, in frequency range 0.5 to 200 Cps, are made for various combinations of natural graphite, electro-graphite, copper, gold, silver, rhodium, mercury, and loose graphite flakes."

68. A. M. Intrator, An Investigation into the Use of Conductive Lubricants for the Reduction of Shaft-Bearing Noise, Naval Civil Engineering Lab., Port Hueneme, Calif., Tech Note N-085, 25 Apr. 1952, (PB 154 635).

"Radio interference has been observed to originate in the shaft-bearing area of some rotating machinery and was attributed to erratic discharge through the shaft lubricant of the static charge developed between the shaft and bearing. A laboratory test set up was designed to study the effectiveness of various conducting lubricants in reducing such interference. None of the lubricants tested offered a sufficiently low impedance path for complete elimination of the noise voltages, although the graphite grease mixtures did lower the measureable noise somewhat."

69. J. Radnick, Investigation of Noise Generated by Electrical Slip Rings, Armour Research Foundation, Apr. 1953, (AD-13054).

"Fundamental investigations of the source mechanisms of electrical slip ring noise under the specific conditions of high ring surface speeds and extremely low current were made for the purpose of developing techniques to obtain consistent and reliable vibration measurements. A literature and patent survey (included as an Appendix) was made for clues to the physical mechanisms contributing to slip ring noise. Noise measurements were carried out to substantiate theoretical predictions. Slip ring noise reduction was attempted by application of voltage and high frequency bias techniques to a representative slip ring brush assembly. It was concluded that the major source of electrical noise at high speeds is the complete separation of brush and slip ring caused by very small irregularities in the ring."

70. G. Forster, Investigation of Noise Generated by Electrical Slip Rings, Armour Research Foundation, Apr. 1954, (AD-51055).

"Strain gage recording of propeller strains was limited by electrical noise produced by the slip rings and contacts. The sources of slip ring noise were found to be thermoelectric effects, variable contact resistance, and loss of contact on brush bounce. The latter was the major offender for the usual form of rigid brush under conditions of high slip ring surface speed. An effective means of

nullifying the causes of bounce is a brush of metal wool which absorbs and damps out mechanical shocks. The material conforms to the slip ring surface so that the contact area remains relatively constant. With the noise of brush bounce eliminated the noise due to variable contact resistance became important. The main cause of this is slip ring film and the materials of ring and brush must be chosen so that film is slow to form and easy to remove. Of the materials tested, a molybdenum wool brush on a silver slip ring was best."

71. B. Horton, Sliding Contacts to Transmit Small Signals, REVIEW OF SCIENTIFIC INVESTMENTS, Vol. 20, pp. 930-932, Dec. 1949.

"Measurements have been made of root-mean-square noise voltage in the frequency range 0.5 to 200 cps by contacts sliding at low speeds using four arrangements of contacting bodies and various materials. Mercury with amalgamated probes gave the lowest noise levels. Some solid contacts operating with low friction on clean metal surfaces yielded values of generated noise below 1 microvolt at a sliding speed of 35 cm/sec when two contacts were in parallel. The noise increases with speed and varies with normal force. The r.m.s. generated noise voltage of a large number of independently mounted contacts in parallel is inversely proportional to the square root of the number of contacts."

72. Study of RFI Tests for Engine Starting Vibration and Relays, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Penna., Dec. 1954.

This report deals with the investigation and elimination of "any errors and ambiguities in the specification test for radio interference characteristics of starting vibrators, remote control switches, and similar equipment, for the purpose of uncovering any undesired factors influencing the accuracy of measurements". Test set-ups and results are shown. Specific recommendations for changes to Specification No. MIL-V-5635 and MIL-C-5439 are included.

73. D. F. Meyers, Traces Radio Noise from Bushing, ELECTRICAL WORLD, Vol. 121, pp. 1260, Apr. 1, 1944.

Describes a series of tests on a 34.5 kv condenser-type bushing installed in a transformer bank. Tests showed strong radio interference when the applied voltage reached 9 kv. It was determined that

interference was due to bad contact between the main flange and the ground layer of the condenser.

MISCELLANEOUS

74. R. L. Baker, Aircraft Position Light Flasher, Seaboard Electric Company, Radio Interference Tests Of, Naval Air Test Center, Patuxent River, Md., 6 Dec. 1957, (AD-150 599).

"A radio interference evaluation was conducted on a type F-1 aircraft position light flasher, Seaboard Electric Company Part No. 3270, to determine compliance with the requirements of specification MIL-I-618B. The flasher failed to meet the requirements of the specification for either conducted or radiated interference. It is recommended that the conducted and radiated interference levels be brought within specification limits by providing more efficient filtering and/or shielding of the interference source."

75. Eliminating RFI, U. S. BUREAU OF SHIPS JOURNAL, Vol. 6, No. 3, pg. 34, July 1957.

Lists a few procedures for eliminating RFI from machine tools.

76. L. W. Thomas, Government Radio Interference Requirements for Machine Tools, TOOLING AND PRODUCTION, Vol. 21, No. 4, July 1955.

77. R. Fraser, Measurements of RFI and Modification on Gomco Suction Apparatus, Electro-Search, Phila. Pa., Aug. 1952, (TIP G U 24418).

"The apparatus consists of a split-phase induction motor and a compressor incorporated within a single housing. Interference was eliminated by confining the radiated energy within the shielding and by filtering out the conducted energy with two HE-1-3115 filters. The modified unit met the requirements of the Navy specifications except for a slightly excessive interference in the 16 Mc region."

78. H. Kenny, Measurements of RFI from Aircraft Position Light Flasher MIL-E-7414 (Type C-2) of Seaboard Electric Co., Electro-Search, Phila., Pa., March 1955, (AD-78643).

79. H. Kenny, Measurements of RFI from Cox-Head-Liner Model CHL-1 of Ralph C. Coxhead Corp., Electro-Search, Phila., Pa., Mar. 1955, (AD-78644).

80. C. D. Fahmkop, Methods of Reducing Radio Interference of Machine Tools, TOOL ENGINEERING, Vol. 35, pp. 196-198, July 1955.

81. Navy Type Meggers--Radio Interference--Analysis of; Letter Report, Navy Electronics Laboratory Report No. 61, 1947.

82. C. D. Emerson, RFI.....Problem of Automatic-Machine Control, AMERICAN MACHINE, Vol. 99, No. 23, pp. 122-125, Nov. 7, 1955.

83. J. Krause, W. Schattler, RFI Tests on Federal Enterprises Horns--Type H4D3, Industrial Specialty Co., March 1954, (AD-53764).

84. J. Krause, W. Schattler, RFI Tests on Federal Enterprises Horn--Type 1C/H4D2, Industrial Specialty Co., March 1954, (AD-53766).

85. E. Birch, H. Craig, RFI Tests on Model H9 S4 Motor Driven Horn, Industrial Specialty Co., Jan. 1954, (AD-53765).

86. C. D. Emerson, L. W. Thomas, Radio Interference--A Problem of Automatic Machine Control, U. S. BUREAU OF SHIPS JOURNAL, Vol. 5, No. 1, pp. 25-29, May 1956.

Briefly describes the Navy requirements and test procedures for contractor supplied equipment capable of generating RFI.

87. Leonard W. Thomas, Radio Interference from Machine Tools, U. S. BUREAU OF SHIPS JOURNAL, Vol. 3, No. 7, pp. 35-38, Nov. 1954.

Outlines the Bureau of Ships specifications for radio interference reduction on machine tools and portable power tools.

88. Suppression of Broadcast Interference from Electric Lifts, British Electrical and Allied Industries Research Association, Rpt. M/T 42, 1935.

89. Test of Electrical Bilge Pump for Radio Interference, U. S. Tank Arsenal Proving Ground, Utica, Mich., Rpt. PG-61705.17, Project 235, Apr. 1944.

"This is a report of a project initiated to obtain installation data and to provide for a radio interference test on electric bilge pumps in an M-4 series medium tank. No result of the radio interference test is given."

CHAPTER VIII

NON-INDUSTRIAL EQUIPMENT INTERFERENCE

GENERAL

In ref. (1), Garlan and Davis state:

> Many of the devices capable of generating man-made noise are operated without licensing under Parts 15 and 18 of the FCC rules. Government restrictions and efforts of industry are doing much to reduce the probability of interference from these devices. Basically the requirements are designed to reduce the level of sky wave radiation on communication channels to a level below that likely to cause interference and to confine ground wave signals to a reasonably short radius.

The technical requirements are also aimed at preventing the transmission of unwanted signals by the power lines.

On a frequency basis, equipment regulated by the FCC can be divided into three categories:

(1) Those which operate in special ISM (Industrial, Scientific and Medical) frequency bands without restrictions on the radiation:

(2) Those which operate on any frequency but with a limitation on the amount of radiation on frequencies outside of the ISM bands;

(3) Those which operate on any frequency except international distress frequency bands with limitations on the amount of radiation.

Typical sources of radio frequency energy, regulated under Part 18, that contribute noise to the radio spectrum are medical diathermy equipment, medical and industrial

ultrasonic equipment, neon signs, garage door openers, and carrier current systems.

BUSINESS MACHINES

With the advent of more and more business machines utilizing electro-mechanical systems and operating in close proximity to sensitive receivers, a potentially serious source of interference has developed. The problem of suppressing this interference was studied by Ruzgis and described in ref. (4). It was determined that the sources of interference were located in the drive motor, its speed governor and the line breaker switch. It was found that radiated interference exceeded permissible levels at distances as great as 100 feet from the machines. Field intensities in excess of 6-8 μv/m/kc were measured in the 100-1000 kc range. Peaks of 10 μv/m/kc at a distance of 20 feet were measured at 40-80 mc with a rapid dropoff to tolerable levels at 100 mc. Conducted interference, measured across the power line, was 60-85 μv/m/kc in the frequency range from 0.1 to 40 mc. Natural shielding from the case of the machine was ineffectual due to part of the housing being constructed of non-metallic material. Complete enclosure of the equipment in shielding material was not deemed feasible because it would interfere with the operation of the equipment. As a result of various tests, the following suppression system was found applicable to most office machines:

(1) Power input leads filtered at point of entry into machine;

(2) Motor field split to permit insertion of a governor circuit between the drive motor brush and field;

(3) Each drive motor brush bypassed with 0.01μfd capacitor;

(4) RC network installed across line breaker points;

(5) Governor points and resistors shunted with a spark absorption capacitor;

(6) Shielding of drive motor, governor points, line breaker points, and interconnecting wiring made RF tight.

MEDICAL ELECTRONIC EQUIPMENT

Interfering signals from medical equipment can be categorized into two broad groups: (1) Broadband interference is characterized by a pulse waveshape having a high energy content over a large portion of the frequency spectrum. A high current switching relay in an X-ray unit would produce this type of interference. (2) Continuous-wave interference generates discrete frequencies as characterized by the diathermy machine harmonics.

In the case of diathermy machines, the primary methods of reducing interference levels are to keep the master oscillator stable and to use adequate shielding. Conducted interference is minimized by means of L-C filters.

Audiometers, essentially audio oscillators, can cause interference with harmonics beyond 100 kc. Filtering is

normally used to suppress the interference. Surgical cutting equipments are spark-gap type devices utilizing high frequency r.f. for cutting. Filtering and shielding techniques are used to suppress the radiated and conducted interference. Ultra-violet quartz lamps produce high levels of radiated interference in the 14 kc range during warmup and the 12 mc range during operation.

In addition to military standards on tolerable limits of interference for this equipment, the Federal Communication Commission has also allocated channels at 13.56, 27.12, 40.68 and 2450 mc with maximum limits of radiation.

APPLIANCES

Strafford states in ref. (32) that domestic appliances using fractional-horsepower commutator motors are the most serious sources of interference in the household. The current, due to the commutating action of the motor, gives rise to a broadband spectrum of interference. The currents are circulated in both a symmetric and asymetric mode. If design could obtain perfect balance so that only the symmetric mode was circulated, very little suppression in the VHF and UHF bands would be required. This is not possible in practical design due to the inherent distributed capacitance.

Practically, the symmetric mode may be suppressed by a shunt capacitor and the asymmetrical mode can be limited by means of series inductances. The inductances are not effective at the higher frequencies because the few inches of

lead between the motor and the inductance can radiate before the asymmetric component is limited. Shielding of the entire unit, if possible, is then the most effective means of reducing interference at the higher frequencies.

CHAPTER VIII
BIBLIOGRAPHY AND ABSTRACTS

GENERAL

1. H. Garlan, E. Davis, Man-Made Noise, Federal Communications Commission, Aug. 1957, (AD-150 771).

The report provides general information on most of the devices that produce man-made noise and which are regulated under Parts 15 and 18 of FCC Regulations. It stresses the effect that the location of these devices can have on satisfactory circuit operation.

BUSINESS MACHINES

2. H. Kenny, Measurements of RFI from Hamann Model 300 Calculating Machine, Electro-Search, Phila., Pa., Aug. 1955, (AD-78645).

3. J. M. Sarley, R. J. Hendery, Radio-Interference Control as Applied to Business Machines, IBM JOURNAL OF RESEARCH AND DEVELOPMENT, Vol. 1, No. 4, pp. 363-372, Oct. 1947.

"This paper discusses sources of radio interference and methods used to reduce the interference levels present in business machines. Particular attention is given to electro-mechanical machines. Testing methods are also considered. A description is given of the development of a universal line filter which has been most successful in reducing noise transmission over power cable. The development of reinforced plastic machine covers creates even greater challenge in radio interference control. A discussion is given of experimental solutions to these future problems through the use of such techniques as copper screening, copper spray, and imbedded metallic foils."

4. Albert Ruzgis, Radio Interference Suppression System Design Considerations for Electric Office Machines, Tech. memo. No. M-1877, Army Signal Engineering Labs, Fort Monmouth, N. J., 8 April 1957, (AD-132 952).

"A business machine's interference producing potentialities and the necessary approaches for development of a suppression system which would conform to Military Specification MIL-I-11748 (SigC) were investigated. Interference which exceeds the permissible levels cited in the specification was found to radiate to distances of at least 100 ft. from

machines which received no interference reduction treatment. The interference radiated from the machines was of such magnitude that the degree of attenuation obtained from bypassing of the power leads was inconsequential. Natural shielding by means of the machine housing could not be employed advantageously since at least a portion of the housing was fabricated of a nonmetallic material. The only components requiring interference reduction considerations were the drive motor, its speed governor, and the line breaker switch. The system for obtaining the required degree of attenuation with the test equipment antenna located at a distance of 50 ft. differed only slightly from the system required when the antenna was located at 20 ft. from the machines."

MEDICAL EQUIPMENT

5. H. Sachs, A. Albin, Control of Radio Interference from Medical Electronic Equipment, Proceedings of 2nd Conference on Radio Interference Reduction, Armour Research Foundation, March 1956.

6. R. L. Haskins, Diathermy Interference, RADIO ENGINEERING, Vol. 15, No. 2, pp. 20-21 and 26, Feb. 1931.

7. Irving Brown, Evaluation and Reduction of Radio Interference Characteristics of Electro-Medical Equipments, Quarterly interim engineering report No. 4, Electro-Search, March 1954, (PB 114 284).

8. P. M. Pickei, Evaluation and Reduction of Radio Interference of Burdick Microwave Diathermy Generator, Model MW-1, Material Lab, New York Naval Shipyard, Brooklyn, 20 Nov. 1957, (AD-161 438).

"The Burdick Microwave Diathermy Generator, Model MW-1 as received does not meet the limits of Spec. MIL-I-16910A (SHIPS) dated 30 Aug. 1954. The incorporation of a simple power line filter in the Burdick Microwave Diathermy Generator could enable the equipment to meet the required limits."

9. K. Oishi, Evaluation and Reduction of Radio Interference on Raytheon Microwave Diathermy Generator Equipment No. KV-104C, Model CMD-10, Material Lab, New York Naval Shipyard, Brooklyn, 11 Jan. 1957, (AD-134 404).

Graphs of radiated and conducted interference from 10 kc to 1000 mc are shown. Conducted interference was reduced below the limits specified in MIL-I-16910 (SHIPS). Radiated interference was

reduced to within limits except in the range between 530 and 1000 mc. This radiated interference came from the shield can surrounding the filament leads of the magnetron oscillator.

10. E. Chapin, W. Roberts, M. Mobley, FCC Diathermy Design for Low Harmonic Radiation and Good Frequency Stability, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 67, pt. 1, pp. 42-46, 1948.

    "This paper sets forth the principles which pertain to the elimination of frequency instability and harmonic radiation from diathermy equipment, illustrating the application of the principles with an actual model. The problem of high frequency harmonics requires facility with high frequency techniques."

11. Interference from Diathermy Apparatus, British Electrical and Allied Industries Research Association, Rpt. M/T 72, 1942.

12. Interference Troubles from Industrial and Medical Apparatus, ELECTRICIAN, Vol. 136, pg. 1172, May 3, 1946.

13. Emil Brou, Medical Electrical Equipment, Testing for Electronics Interference, Burdick Microwave Diathermy Equipment, Model MW-1, Medical Equipment Development Lab. Fort Totten, N. Y., Memo Rpt. No. 58-3, 24 Feb. 1958, (AD-159 125).

14. K. G. Jansky, Minimum Noise Levels Obtained on Short-Wave Radio Receiving System: Effect of Diathermy Machines, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 25, pp. 1517-30, Dec. 1937, Correction Vol. 26, pg. 400, April 1938.

    Generally discusses noise levels in receivers. The second portion of the report deals with measurements of diathermy interference. The worst interference was found on 16.7 meters in comparison with 32.2 meters and 14 meters. Frequency of some of the machines would vary irrationally by at least as much as 200 kc.

15. Erwin Levey, Radio Interference Measurements and Modifications on Audiometer Equipments (Stock No. 3-074-100), Electro-Search, April 1952, (PB 107 102).

    "In this work the unit was considered as both a source and a receiver of interference. For the equipment considered a source of interference, each cause of interference was analyzed separately and

the methods employed either to reduce or completely eliminate it are discussed in detail. For the equipment considered a receiver of interference, a similar type of analysis is made in terms of the specific problems encountered in this phase of the work."

16. Erwin Levey, Radio Interference Measurements and Modifications on Burdick Model MF-49 Diathermy, Electro-Search July 1952, (PB 108 051).

"This report gives a detailed analysis of RFI tests performed on a Burdick MF-49 diathermy unit. In this work the unit was considered a source of interference. This interference is due to radiation and conduction of energy on the fundamental frequency and on harmonics. Various methods and techniques were tried to reduce the harmonic interference, and these are described in the report."

17. Erwin Levey, Radio Interference Measurements and Modifications on Electrosurgical Unit, Portable (Stock No. 3-275-600), Electro-Search, Aug. 1952, (PB 108 283).

"...gives detailed analysis of r-i tests performed on unit. Unit was found to be a source of considerable interference. RFI reduction methods described in detail."

18. James H. Ray, Radio Interference Measurements and Modifications on Fischer Model 'ANM' X-Ray Unit, Stock No. 6-124-885, Electro-Search, Tech Rpt. 158, June 1954, (PB 117 540).

"A description of the radio interference tests performed on an X-ray unit is given. The modifications which were made to reduce this interference are discussed, and those which are considered to be most adaptable to production techniques are recommended."

19. Simon Kravitz, Radio Interference Measurements and Modifications on Liebel-Florsheim Model SW-660 Diathermy, Electro-Search, Sept. 1952, (PB 108 053).

"The investigation involved a series of radio interference measurements that indicated the initial quantity of electrical noise emanating from the diathermy unit. Thereafter, an extensive series of modification attempts were embarked upon to reduce the radio interference. The discussion and tabulation of measurements thereon and subsequent

modifications are presented in the report."

20. H. Kenny, RFI Measurements and Modifications on Neuro-Surgical Stimulator (Stock No. 3-743-500), Electro-Search, June 1953, (AD-20652).

21. H. Kenny, RFI Measurements and Modifications on "Walker" Opthalmic High Frequency Unit (Stock No. 3-533-100), Electro-Search, May 1953, (AD-20651).

22. E. Levey, RFI Measurements and Modifications on Ritter Birch Type Dental Unit (Stock No. 5-252-500), Electro-Search, Apr. 1953, (AD-20560).

23. C. W. Sowton, G. A. C. R. Britton, Radio Interference Industrial, Scientific and Medical Apparatus and Radiating Receivers, POST OFFICE ELECTRICAL ENGINEERS JOURNAL, Vol. 51, pt. 3, pp. 202-205, Oct. 1958.

24. Radio Therapy: Measures to be Taken to Prevent Interference with Radio Communication, SCIENCE, Vol. 84, sup. 8, Dec. 11, 1936.

25. Report on Radio Interference from Electro-Therapeutic Apparatus, Section 12, Inter-American Arrangement Concerning Radar Communications, Federal Communications Commission, Dec. 1937.

26. W. C. Stoker, Wm. W. Seifert, Shielding for Diathermy, Rensselaer Polytechnic Institute, Oct. 1943, (PB L 86389).

"This report deals with the problem of preventing interfering radiation from r-f power equipment used for non-communication purposes. The general factors affecting the coordination of electrical facilities, namely, the influence factor, the coupling factor, and the susceptibility factor are shown to apply to the problem. Means for controlling the first and third factors are briefly discussed. The major portion of the report is concerned with the coupling factor. The three shielded room types: single, double coupled and cell type (parallel) are compared on a basis of cost, attenuation and attenuation per dollar cost. It is concluded that comparatively cheap, semi-portable shielded rooms can be made and equipped with effective filters to produce attenuation ranging from 73 db (single shield) to 140 db (double shield)."

27. W. Nethercot, Short-Wave Radio Interference Produced by Electrotherapy Apparatus, British Electrical and Allied

Industries Research Association, Rpt. M/T 50, 1937.

28. H. M. Sachs, A. L. Albin, Suppressing Radiation from Medical Electronic Equipment, ELECTRONIC INDUSTRIES AND TELE-TECH, Vol. 15, pp. 68-70, Nov. 1956.

"The problems of generation and susceptibility to interference signals are solved at the source. Filters and enclosure shielding are used by designer. Data on these and other methods are presented. The type of interference created by specific medical equipment is also discussed."

29. E. F. H. Gould, Suppression of Radio Interference from Electro-Medical and Certain other Types of High Frequency Apparatus, POST OFFICE ELECTRICAL ENGINEERS JOURNAL, Vol. 35, pt. 1, pp. 23-27, April 1942; ELECTRONIC ENGINEERING, Vol. 15, pg. 284, June 1942.

30. Suppression of Radio Inductive Interference from Electro-Medical Apparatus, Part of Report on Radio Interference from Electro-Therapeutic Apparatus, Canadian Delegation to the Inter-American Regional Conf., Havana, Cuba, Nov. 1937.

APPLIANCES

31. E. Pawley, Appliances and Radio Interference, ELECTRICIAN, Vol. 132, No. 3444, pp. 475-476, 2 June 1944; WIRELESS WORLD, Vol. 50, No. 8, Aug. 1944.

"Shorter wavelengths require careful techniques. Single phase series wound motors are serious offenders and should be replaced by 3 phase according to the author. However, there are many practical disadvantages to 3 phase in the home, i.e. high voltage, more wiring, etc."

32. F. R. W. Strafford, Band III Television Interference, WIRELESS WORLD, Vol. 60, pp. 501-504, Oct. 1954.

"Discusses the interference generated by household appliances in the TV bands. Discusses various methods of suppression and their limitations. Suggests the desirability of reducing interference at the design stage of the motor."

33. R. L. Hoskins, C. W. Metcalf, Control of Radio Noise Can Enhance Appliance Load, ELECTRONIC WORLD, Vol. 109, pp. 1191-1192, Apr. 9, 1938.

"Discusses composition of radio noise voltages

from electrical appliances. Diagrams and test procedures for investigating the RFI are shown."

34. J. W. Teegarden, Household Radio Interference Eliminators, RADIO AND TELEVISION NEWS, Vol. 42, pp. 34-35, Sept. 1949.

To be effective the filter must be placed on the equipment which is the cause of the radio interference. Methods of suppression of household appliances are discussed. The problem of household filtering is finding the true earth ground or satisfactory reference point.

35. F. R. W. Strafford, R. R. Teesdale, Inductor Suppressors, WIRELESS WORLD, Vol. 60, No. 1, pp. 15-16, Jan. 1954.

Discusses the use of small inductors mounted in the power leads fairly close to the appliance as a means of suppressing electrical interference.

36. Coombes, Interference from Electric Razors, ELECTRICAL REVIEW, Vol. 125, pg. 396, Sept. 22, 1939.

37. Interference from Thermostats, Refrigeration and Irons, British Electrical and Allied Industries Research Association, 1938.

38. F. A. Thebridge, Interference Suppression in Household Appliances, INSTITUTION OF RADIO ENGINEERS (AUSTRALIA) PROCEEDINGS, Vol. 21, No. 9, pp. 577-580, Sept. 1960.

39. Noise from Heating Pads, QST, pg. 67, Oct. 1950.

Briefly discusses methods of by-passing each of the thermostats in a heating pad with small condensers.

40. Radio Interference from Common Appliances, U. S. BUREAU OF SHIPS JOURNAL, Vol. 5, No. 8, pg. 34, Dec. 1956.

Motors, dynamotors, inverters, fluorescent lights, business machines, coding machines, electrical appliances, electric razors, and electric erasers are listed as possible sources of RFI. Unless attenuated by filters, interference is impressed on power lines and then conducted to receivers.

41. Suppression of Appliances and Small Motors, Air Services Telecommunication Division, Dept. of Transport, Canada, Circular S11-10-1, June 1956.

42. S. F. Pearce, Suppression of Radio Interference from Electrical Appliances, BEAMA JOURNAL (London), Vol. 54, pp. 40-47, Feb. 1947.

43. L. H. Daniel, S. Whitehead, Suppression of Radio Interference with Particular Reference to Portable Appliances, British Electrical and Allied Industries Research Association, Rpt. M/T 52, 1938.

44. Type Testing for the Interfering Voltages of Small Electric Appliances, British Electrical and Allied Industries Research Association, Rpt. M/T 59, 1938.

45. C. W. Frick, Your Product Need Not Cause Radio Interference, ELECTRICAL MANUFACTURING, Vol. 23, No. 3, pp. 31-34 and 60, March 1939.

MISCELLANEOUS

46. Control of Radio Interference from Industrial, Scientific and Medical Equipment, Air Services Telecommunication Division, Department of Transport, Canada, S 11-13-29, Feb. 1953.

47. J. R. Steen, Eliminating Traffic Signal Noise in Radio Receiving Sets, RADIO NEWS, Vol. 17, pg. 536, Mar. 1936.

48. J. Deitz, FCC Control of RFI, ELECTRONIC DESIGN, Vol. 8, No. 7, pp. 56-59, 30 March 1960.

"Restricted radiation devices, incidental radiation devices, and industrial scientific and medical equipment must be designed to prevent radio frequency interference. The radiation limits for these devices are specified by the FCC in Part 15 and Part 18 of the regulations. The technical requirements of these regulations are discussed and part of the tables are reproduced to illustrate the text."

49. Incidental and Restricted Radiation Devices, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 44, pg. 436, March 1956.

"A report of the Appendix to Docket No. 9288 of the Federal Communications Commission giving the amended FCC rules governing restricted radiation devices."

50. F. R. W. Strafford, Interference from Neon Signs. Its Cause and Cure, WIRELESS WORLD, Vol. 42, pp. 458-460, May 26, 1938.

"The actual mechanism whereby RF oscillations are produced in a neon tube circuit has hitherto been obscure. The author of this article shows that the necessary conditions for oscillation exist in a typical neon sign and its associated wiring; he goes on to discuss means of preventing the radiation of interference."

51. Measurement of Field Intensity Above 300 Mc from H-F Industrial, Scientific and Medical Equipment, American Institute of Electrical Engineers, AIEE Standards No. 950.

52. Rules and Regulations Relating to Industrial, Scientific and Medical Service, Federal Communications Commission (Washington, D. C.), Title 47, Telecommunication, Chapter I, part 18, 1947.

53. 16 MM Sound Motion Picture Projection System, De Vry Corp., Investigation for Suppression of RF Noise, Material Lab, New York Naval Shipyard, Brooklyn, Jan. 1950, (TIP G U 13035).

"The projector unit was modified for the suppression of RF noise by (1) the removal of filters in the drive motor circuit, (2) connection of 0.01 microfarads capacitor between the leads to the drive motor and ground, (3) insertion of tube filterettes in the a.c. power-line circuit, and (4) substitution of shielded wire in exciter-lamp circuits. Changes were also made in the amplifier unit. The conducted RF noise measured less than 5 microvolts after the changes; radiated noise measured 300 microvolts at 190 and 380 Kc."

CHAPTER IX

RADIATION HAZARDS

INTRODUCTION

The disruption of communications and low-level electromagnetic measurements is not the only problem introduced by undesired or uncontrolled electromagnetic radiation. Actual physical hazards to personnel and explosive hazards to ordnance and fuels exist in the vicinity of radio frequency radiators.

PERSONNEL HAZARDS

Prior to World War II there were very few installations at which r-f radiation was at a high enough level to be considered a hazard to personnel. However, since that period, transmitter power outputs have been increased to the order of megawatts for several radars and radio facilities.

Charles I. Barron, M. D., discusses the areas of the human and animal body that are susceptible to damage by electromagnetic radiation in ref. (3). The areas of main concern are the eyes, the blood, the testicles, and the nervous system.

There are two distinct hazards to the human body. The greatest harm to human beings is the heating effect due to r-f radiation. In ref. (6) William L. Bunch, Jr. points out that the total heating effect is a function of the field intensity, distance from the antenna, the transmitted frequency,

the exposure time in the r-f field, the ability of the human body to dissipate heat, and the climatic conditions at the time of exposure. Radio frequency radiation in the frequency range of 200 to 3,000 megacycles penetrates deeply into body tissues, whereas high frequencies (3,000 to 11,000 mc) produce heating at or near the surface of the body. Since most of the sensory nerves of the body are concentrated at the surface, it is entirely possible that the general warming of the body will not be perceived before damage is done. At the higher frequencies, the heating discomfort can be felt by an individual.

The second hazard to the body, tissue ionization, is discussed in ref. (4). This damage, normally associated with frequencies of $3x10^{15}$ to $3x10^{18}$ cps, cannot be perceived at time of exposure. Frequencies in this range are not purposely generated in common electronic equipment, but they can result as undesirable by-products. The power level required to produce damaging effects from this X-radiation is much lower than that for producing heating.

Many organizations have made studies to determine the acceptable limits of exposure for personnel. The acceptable tolerances for the U. S. Navy, determined by the Bureau of Medicine and Surgery, have been established as 0.01 watts per square centimeter for r-f heating energy and at 0.3 roentgens per week for ionizing radiation. Ref. (7) reviews the safety criteria established by the Bell System and also

points out some of the difficulties encountered in establishing such criteria. In general, the armed services have established higher tolerance levels than industrial firms.

ORDNANCE HAZARDS

Russell N. Skelters outlines some of the known history of electromagnetic radiation hazards to ordnance in ref. (29). One of the first published accounts of a blasting accident attributed to radio transmission was by E. I. du Pont de Nemours and Co. in 1949. Several cases of premature ignition of rocket motors were known in the U. S. Navy before 1957. At that time two projects were started, the RAD HAZ (Radiation Hazards) program under the Bureau of Ships and the HERO (Hazards of Electromagnetic Radiation to Ordnance) program under the Bureau of Naval Weapons. Presently all the armed services are interested in such hazards. However, the problem is not restricted to military weapons. Construction companies using r-f initiated blasting caps take precautions to ensure that no radio transmitters are used near blasting sites.

The RAD HAZ program, outlined in ref. (33) is more comprehensive than the HERO program. The former also covers hazards to personnel and fuels.

In ref. (21), Richard E. Grove explains the reason for the incompatibility between electromagnetic fields and many modern day ordnance systems. These ordnance devices rely on electroexplosive devices (EED's) to provide electrical

switching, to actuate and perform mechanical functions, and to ignite explosive and propulsive sequences. Two types of EED's are in common use: the wire bridge initiator and the carbon bridge initiator. In the wire bridge initiator, a fine wire is heated by energy from the firing circuits. A small bead of temperature-sensitive explosive is positioned near the fine wire and is used to initiate the explosive sequence. The carbon bridge initiator, which is even more sensitive than the wire bridge, utilizes a thin film of polycrystalline carbon deposited on an insulating substrate. When energy is applied to the carbon bridge, it is thought that sparking between adjacent crystallites and Joule heating initiates the explosion. Lead wires to both of these types of initiators are believed to act as antennas in picking up extraneous electromagnetic radiation and thereby causing firing of weapons.

Several testing procedures that have been used to determine the level of susceptibility of various weapons to an electromagnetic environment are also described in ref. (21). The earliest tests were "go/no-go" tests in which a weapon, with explosives removed, was placed in a known electromagnetic field. The various parameters considered were frequency of radiation, transmitter power, distance from the transmitter antenna, and weapon orientation with respect to the antenna. Radiation levels were increased until the EED's were initiated. This proved time consuming and expensive;

large numbers of tests had to be performed before a reliable statistical statement of firing characteristics could be made.

Attempts have been made to replace actual EED's with instrumented EED's. These attempts have not been completely successful because the electrical characteristics of the EED's have not been fully duplicated. Three major types of EED instrumentation that have been used are radiation thermocouples, thermistors, and sensitive resistance measuring devices.

The principle measure taken to eliminate undesired activation of EED's has been to provide an electromagnetic shield to the EED's. A proposed specification for such shielding is given in ref. (31). The basic features of the proposed specification include an electrically continuous metallic enclosure, only "wave guide below cut-off" holes in the shield, separation of EED firing circuit conductors from other weapon component conductors, and shielding of conductors. The use of low-pass filters to protect EED's is proposed in ref. (38), however, no tests are reported.

FUEL HAZARDS

It is quite elementary that sparking in the presence of a volatile gas is hazardous. Large amounts of volatile gas are generated in practically all refueling operations. Several references in earlier sections of this chapter have pointed out that sparking can be produced by radio frequency

electromagnetic fields. Both radio frequency electromagnetic fields and refueling operations are found aboard ships and at air facilities. Ref. (44) describes tests which were performed at Rome Air Development Center to determine the actual hazard created by refueling aircraft in an electromagnetic environment. In general, it was found that at distances greater than 100 feet radio frequency radiation arcing caused by an AN/FPS-6 radar did not constitute a hazard to volatile gases.

O. B. Rawls, et al, report in ref. (41) that the U. S. Air Force has established a critical power density of 5 watts/sq. cm. peak which must not be exceeded in locations where fueling operations are in progress. This standard is relatively high because it was established under ideal conditions. However, if it is observed, it leads to a higher factor of safety. In contrast to ref. (44), this report states that an AN/FPS-6 radar would cause a fueling hazard at distances of up to 2500 feet. Hazardous distances for other radars are also listed.

Some of the factors which determine if an explosive hazard exists are richness of fuel-air mixture, air temperature, type of configuration acting as an antenna, gap width where sparking occurs, pulse width and repetition rate of r-f source, frequency, and field intensity of the electromagnetic radiation. Considering all these factors, it can be seen that making predictions of the existence of explosive

hazards is quite complicated. Any instrument designed to measure the presence of explosive hazards would need to take these factors into account. No references were found that work was being pursued in this area.

CHAPTER IX
BIBLIOGRAPHY AND ABSTRACTS

PERSONNEL HAZARDS

1. Charles L. Stec, Electromagnetic Radiation Hazards, U. S. BUREAU OF SHIPS JOURNAL, Vol. 6, pg. 32-33, Aug. 1957.

   The personnel hazards from electromagnetic radiation are discussed for frequencies from 60 to 10^{25} cps. Heating effects and ionizing effects are included.

2. Russell L. Carpenter, An Experimental Study of the Biological Effects of Microwave Radiation in Relation to the Eye, Tufts Univ., Medford, Mass., Feb. 28, 1962, (AD-275 840).

3. Charles I. Barron, Physical Evaluation of Personnel Exposed to Microwave Emanations, Lockheed Aircraft Corp., 1955, (AD-63 851).

   This report briefly reviews results of experiments performed to evaluate the effects of electromagnetic radiation on the eyes, blood, nervous system, and testicles of animals. It then describes a program which was undertaken at Lockheed Aircraft Corp. to evaluate the effects of microwave radiation on personnel. Results of the program after six to nine months are given.

4. Radiation Hazards in Naval Electronic Equipment, U. S. BUREAU OF SHIPS JOURNAL, Vol. 10, pg. 33, Jan. 1961.

   Two types of hazards are covered:
   (1) RF radiation (= 1 to 10^6cm) -- causes heating of body
   (2) X-radiation (= 1×10^{-7} to 1×10^{-10} cm) -- causes ionization of body tissues. Less power is required for this than for RF damage. X-ray dose limit was set at 0.3 R/week.

   Devices in which electrons are accelerated by voltages greater than 25,000 volts required lead shielding. Methods of detecting RF radiation also are discussed.

5. O. M. Salati, A. Anne, H. P. Schwan, Radio Frequency Radiation Hazards, ELECTRONIC INDUSTRIES, Vol. 21, pg. 96, Nov. 1962.

   "The presently known harmful effects of excessive

radiation are strictly thermal in nature, and a rise in body temperature of 1° is taken as intolerable. In analyzing the amount of radiation that can be withstood, the considerations are the amount of heat that the human body can dissipate, the dosage rate and the length of time of exposure."

6. William L. Bunch, Jr., RF Radiation Hazards, U. S. BUREAU OF SHIPS JOURNAL, Vol. 10, pg. 10, Oct. 1961.

RF radiation was not considered hazardous to personnel until high-power was used in W.W. II. BUMED established tolerance of 0.01 w/cm². A table gives minimum distances to antennas of various equipment. Greatest harm to people is heat. Heat is a function of field intensity, distance, frequency, exposure time, ability of body to dissipate heat, and climatic conditions when exposed. Frequency determines penetration: 200-3000 Mc penetrate deeply, 3000-11,000 Mc heats surface. In most cases, damage to tissues is done before heating effect can be felt.
Critical power density for damage:
Eyes - 0.1 w/cm²
Testicles - 0.005 to 0.01 w/cm²

7. W. W. Mumford, Some technical Aspects of Microwave Radiation Hazards, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 49, pp. 446-7, Feb. 1961.

"This paper reviews the history of the recognition of this potential hazard and safety measures adopted by the Bell System and others to protect personnel. Some typical and pertinent research work is discussed, and it is shown how these results have influenced the establishment of criteria for safe and potential hazardous environments for human beings. The currently adopted safety limits of the Bell System and others are reviewed in some detail, and a recommended method of calculating power densities is derived, pointing out the limitations of the approximations used. Some of the commercially available power density meters are mentioned. and their method of operation is described. Their use in surveying a site is discussed, and the shielding effect of wire mesh fences is presented in a nomograph."

8. R. Haitch, RFI: Invisible Killer?, SATURDAY EVENING POST, Vol. 234, pp. 38-94, Sept. 30, 1961.

9. C. Goode, I. Kabik, Characterization of Squib MK 1 Mod 0: 5 Mc RF Sensitivity for Long Duration Pulses, Naval Ordnance Laboratory, April 24, 1961.

The test procedures, equipment, and results are described for determining the 50 percent fire level for this electro-explosive device. The effects of current amplitude and pulse width are studied.

10. I. Kabik, C. Goode, Characterization of Squib MK 1 Mod 0: Sensitivity to 9 kMc Radar Pulses, Naval Ordnance Lab. Tech. Rpt. 62-77, Aug 31, 1962.

"Mk 1 Mod 0 Squibs were fired in the waveguide of a 9kMc radar. For fully loaded squibs, on the basis of previous tests at D.C. to 5 Mc, the bridgewire in the 9 kMc tests did not reach the temperature expected necessary for firing. Squibs without cup or base charge approximated the expected firing temperature. From the results it is inferred that squib simulators used to predict firing on the basis of bridgewire temperature may not be applicable at frequencies as high as 9 kMc. It is also hypothesized that the powder charges in some devices may act as attenuators somewhat reducing the probability of firing in high frequency RF fields."

11. L. D. Hampton, J. N. Ayres, Characterization of Squib MK 1 Mod 0: Thermal Stacking from Radar-like Pulses, Naval Ordnance Lab., Sept. 1961.

"The electro-thermal equations describing the heating and cooling of wire-bridge electro-explosive devices are solved for constant-current radar-type input pulses. The bridge-wire temperature-time history is obtained for a variety of pulse amplitudes and repetition frequencies. Equilibrium temperatures are obtained for varied input conditions and are all combined in a single nomograph... The conditions for explosion are deduced...."

12. R. A. Dietrich, L. A. Dignazio, Description of Manufacture for Plug, Detonator, T-24EL, R-F, Protective, Atlas Chemical Industries, Inc., Tamaqua, Pa., Aug. 1, 1961, (AD-266 429).

13. Russell N. Skeeters, Design Techniques to Reduce the Hazard of Inadvertent Firing in Electroexplosive Devices by Electromagnetic Energy, Naval Ordnance Test Station, China Lake, Calif., Rpt. No. NOTS TP 2629, March 1, 1961, (AD-256 949).

"Accidental firings of electroexplosive devices can result from electrical sources such as static discharges, sneak currents, and currents generated by thermoelectric action, galvanic action, and electromagnetic induction. Military propellants, explosives, and explosive devices use electrical initiation almost exclusively and hence are subject to inadvertent actuation by spurious electrical currents. It is incumbent upon designers of ordnance to inform themselves of these potentialities and to incorporate into the designs of weapons and weapon systems measures for protection against such accidents. Methods devised or proposed for alleviation of electromagnetic hazards are discussed, and suggestions are made for the incorporation of preventive measures in the initial design of weapon systems."

14. Paul F. Mohrbach, Robert F. Wood, Development of Broad-Band Electromagnetic Absorbers for Electro-Explosive Devices, Laboratories for Research and Development, Franklin Institute, Phila., Pa., Monthly Progress Rept., Oct. 1-31, 1961, (Conf. Report), (AD-327 614).

15. F. Triola, H. Brueckmann, The Effect of Radio Waves on Electrical Blasting, Army Signal Corps Engineering Lab., Aug. 1953, (AD-19 504).

16. M. M. Abromavage, C. C. Merchant, L. de Pian, Electromagnetic Coupling to Ordnance Systems, Jansky and Bailey, Inc., Washington, D. C., Aug. 25, 1961, (AD-265 473).

"Experimental and analytical procedures are presented for the measurement and analysis of transmission of energy from electromagnetic radiators to electrically initiated devices of ordnance systems. Several methods of analysis are presented which are applicable to the transmission of energy along electric circuits from the exterior to the interior of the ordnance device. A method is also presented which applies to the direct entry of electromagnetic wave energy into the interior of a missile through openings in the missile body, such as arming hatches, radomes, and others. A section is included which gives the magnitude of the sum of the radiation and quadrature components of the electric field produced by vertical radiators in a form which is especially useful for computing the hazards of electromagnetic radiation to ordnance (HERO)."

17. W. L. Teeter, B. Wend, et al., Electromagnetic Energy Hazards to the 2.75 inch FFAR Rocket, Navy Electronics

Lab., Rpt. 722, Sept. 17, 1956.

18. D. Shaw, Exposure Tests of RF Attenuated Electric Initiator Aboard the Aircraft Carrier U. S. S. Bon Homme Richard, Feltman Research and Engineering Lab., June, 1960, (Conf. Report), (AD-317 238).

19. Ernest E. Mason, Dorothy H. Zehmer, Hazards of Electromagnetic Radiation to Ordnance. The Development of Techniques to Detect and Determine the Effects of Heat on Selected Primary Explosives, Naval Weapons Station, Yorktown, Va., Progress Rpt. No. 1, Jan. 22, 1962, (AD-277 413 (k)).

20. R. Skeeters. HERO Quarterly Progress on NAVDVPNLAB Task Assignment, PO-1-005, Naval Ordnance Test Station, Dec.1, 1960 through Feb. 28, 1961, (Conf. Report), (AD-322 785).

21. Richard E. Grove, HERO Testing. Techniques and Procedures, Naval Weapons Lab, Dahlgren, Va., NWL Tech. memo W-20/60, Sept. 1960, (AD-242 910).

"A major responsibility of the Navy's HERO program is to predict and evaluate the hazards presented to ordnance by electromagnetic radiation from the fleet's shore, shipboard, and airborne transmitters. This memorandum has reviewed the concepts and procedures that have evolved in the first two years of the organized HERO program for the evaluation of these hazards. The problem will be a continuing one because of the evolution of new weapon systems and because of the need to evaluate the effectiveness of techniques designed to reduce the susceptibility of weapons to electromagnetic radiation."

22. T. Sueta, Interim Report of Radio Wave on Electrical Blasting, Signal Corps Engineering Lab., Sept. 1952.

23. L. Lysher, Investigation of Electromagnetic Hazards to the Guided Missile Complete Round MK 6 Mod 0 (Terrier BW-1) on Board the USS Providence (CLG-6), Naval Weapons Lab., Dahlgren, Va., March, 1960, (Conf. Report), (AD-315 623).

24. Martin M. Abromavage, Investigation of Electromagnetic Hazards to Ordnance at the U. S. Naval Weapons Lab., Dahlgren, Va., Jansky and Bailey, Inc., Alexandria, Va., May 30, 1961, (AD-257 289).

"An explanation is given of procedures used in the measurement and analysis of electromagnetic energy inadvertently delivered to electroexplosive devices

tested at the Naval Weapons Laboratory, Dahlgren, Virginia. The hazards of electromagnetic radiation to ordnance devices are associated with the radiated power transmitted from antennas, environmental field strength magnitudes, RF voltage picked up by exposed firing cables, the RF impedance of the firing circuit, and the terminating impedance of the circuit. It was concluded that a possible hazardous condition existed in the CAD area at the Naval Weapons Laboratory."

25. Investigation of Electromagnetic Radiation Hazards To Regulus I Missile Booster Igniter Aboard the USS Helena (CA-75), Naval Weapons Lab., Dahlgren, Va., Oct. 1959, (Conf. Report), (AD-312 863).

26. C. Hinkle, W. Gilbertson, Investigation of Electromagnetic Hazards to Terrier BT-3 and BW-1 Missiles on Board the USS Dewey (DLG-14), Naval Weapons Lab., Dahlgren, Va., May, 1960, (Conf. Report), (AD-316 676).

27. P. C. Cerstant, B. L. Rhodes, G. E. Chambers, Investigation of Premature Explosions of Electroexplosive Devices and Systems by Electromagnetic Radiation Energy, Midwest Research Institute, Kansas City, Missouri, April 1962, (AD-275 302).

28. E. R. Longman, Investigation of the Radio Frequency Hazards to Case Ignition Primers of 5"/38, 6"/47 and 8"/55 Fixed Ammunition, Naval Research Lab., R-3132, June 1947.

29. Russell N. Skeeters, Near Fields and Ordnance Hazards, Naval Ordnance Test Station, China Lake, Calif., Rpt. No. NOTS TP 2543, Jan. 1961, (AD-253 427).

"The electric and magnetic fields surrounding a vertical antenna are discussed. Information obtained on this subject is applied to the problems of reducing radiation hazards to ordnance."

30. R. N. Skeeters, The Prevention of Accidental Firing, by Induced R.F. Energy, of Rockets in the Aero 7D Launcher, Naval Ordnance Test Station, China Lake, Calif., Rpt. No. NOTS TP 2735, Nov. 1961, (Conf. Report), (AD-326 662).

"The final phase of development and the evaluation tests of a fix for the radio frequency (RF) susceptibility of the 2.75-in. folding-fin aircraft rocket in the Aero launcher are reported."

31. R. R. Potter, Proposed Naval Weapons Requirements. Weapon Design Requirements to Preclude Hazards from

Environmental Electromagnetic Fields, Naval Weapons Lab, Dahlgren, Va., Tech. memo No. W/2-61, Jan. 1961, (AD-249 730).

"An investigation is presented on the hazards of electromagnetic radiation to ordnance (HERO). The purpose of this research is to present in the format of naval weapons requirements a proposed standard of good engineering practices to be followed by designers of future weapons to preclude hazards to electro-explosive devices contained in weapons and weapon systems from environmental radio-frequency electromagnetic fields.

32. Quantum Detector for Measurement of EED Bridge Wire Temperature Rise, Measurement Systems, Inc., Norwalk, Conn. Monthly Progress Rept. No. 1, Aug. 1, 1961 (AD-261 362) and Monthly Progress Rept. No. 3, Oct. 1, 1961 (AD-264 727).

"Research is concerned with the development of a small quantum detector of such size and shape that it can be mounted inside the cavity of an inert or simulated EED Electroexplosive device, such as the MK 1 Squib, to monitor the temperature rise of the EED bridge wire when the EED is placed in an electromagnetic field. Design objective is to sense a temperature rise in the bridge wire of 2 C above ambient, with a signal-to-noise ratio of 6 db, and a time constant of less than 100 microseconds. Investigations in the following areas were initiated or completed: (1) to determine which types of existing detector materials could be used, (2) to determine optimum signal-to-noise ratios for various detectors as a function of identical detector and bridge wire temperatures. (3) to determine the feasibility of using a cryogenically cooled detector, and (4) to determine type of chopper best suited for this application. Investigations were continued on (1) the energy density and quality of images produced by cylindrical and spherical mirrors, (2) the optical condensing system, (3) the feasibility of using fiber optics, (4) the optimum PbS detector, and (5) the design of a vibrating reed chopper."

33. RAD HAZ Program, U. S. BUREAU OF SHIPS JOURNAL, Vol. 8, pg. 31, Sept. 1959.

This article briefly describes the scope of the RAD HAZ (radiation hazards) program and gives a short history of why the program was instituted.

Mention is made of the premature firing of rockets, sparking from loading hooks and aircraft tie-downs, and spark ignition of volatile materials. The investigation of personnel hazards are also discussed.

34. P. C. Constant, Jr., E. J. Martin, Jr., The Radiation Hazards (RAD HAZ) Program on the Formulation of Standards, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, RFI-5, pp. 56-76, March 1963.

"The over-all approach taken in the preparation of RF radiation hazard standards and some basic studies in the area of RF measurement instrumentation are treated in generalities. Specific problems which need to be investigated before final standards can be formulated are delineated. Emphasis is placed on the evolution and composition of radiation hazard standards, RF radiation instrumentation, electromagnetic wave propagation in the 'near field' and RF field intensity sensors. Sensor investigations discussed cover the Hall effect and the pearl chain phenomenon."
Several tables are included which present tolerable levels of RF radiation as recommended by some investigators. Eighty-eight references are also given.

35. J. Bankton, R. Curtis, R. Skeeters, Radiation Hazard Tests Conducted Aboard USS Bon Homme Richard, Naval Ordnance Test Station, Oct. 1959, (AD-312 746).

36. R. H. Stange, Radiation Hazard Tests Performed on the Project Success Depth Charge WOX-3B, Naval Ordnance Lab. White Oak, Md., Nov. 1961, (Conf. Report), (AD-327 865L).

"Radiation hazard tests were performed on the depth charge WOX-3B to determine the susceptibility of the many electro-explosive devices (EED's) in the weapon to spurious initiation of electromagnetic radiation (EMR). The tests were instrumented by monitoring EED bridgewires using diode voltage detectors and thermocouple current detectors. The weapon proved to be vulnerable to EMR exposure. Proper shielding and loading procedures should reduce, to an acceptable level, the likelihood of EED prematures owing to weapon exposure to EMR."

37. Radio Frequency Radiation Hazards, U. S. Air Force Handbook T. O. 31-1-80, April 15, 1958, (revised Aug. 15, 1958).

38. I. Kabik, L. A. Rosenthal, A. D. Solem, The Response of Electro-Explosive Devices to Transient Electrical Pulses, Naval Ordnance Lab., April 1961.

The electroexplosive device is viewed as an energy transducer converting electrical input energies into heat in the explosive system. The basic thermal equation governing the behavior of the device is given and solved for inputs of constant current, capacitor discharge, 5 mc r.f., and typical radar input energies. The solutions are found to compare favorably with experimental firings of the squib Mk 1 Mod 0.

39. Paul F. Mohrbach, Robert F. Wood, RF Attenuating Material Studies. Development of Broad-Band Electromagnetic Absorbers for Electro-Explosive Devices, Laboratories for Research and Development, Franklin Institute, Phila., Pa., Sept. 30, 1961, (Conf. Report), (AD-327 576).

40. Russell N. Skeeters, RF Filters as Radiation-Hazard Suppressors, Naval Ordnance Test Station, China Lake, Calif. Dec. 1961, (AD-271 117).

"One of the techniques used in protecting ordnance from accidental initiation by radio frequency currents is to place a low-pass filter in front of the electroexplosive device. The task of designing filters for this purpose, using the procedures based upon transmission line theory, is tedious and dificult to realize. An analysis is presented of some elementary low-pass filters which points out implications of their loss-characteristic equations for the design of radiation-hazard-suppressing filters."

41. O. B. Rawls, R. J. Stilwell, B. M. McDonald, RF Radiation Hazards. Air Force Missile Test Center, Ordnance--Bio-Effects--Fuel, RCA Service Co., Inc., Patrick Air Force Base, Florida, July 1961, (AD-260 721).

"An analysis of Air Force Missile Test Center radiation sources, which constitute potential radiation hazards, is discussed. The analysis is in three parts; Parts I, II, and III deal with ordnance, bio-effects and fuel, respectively. Within Parts I, II, and III, tabulations have been included which show the extent of hazardous radiation to ordnance for each missile complex; the areas dangerous to personnel; and the areas surrounding the individual instrumentation systems within which fueling operations may be dangerous when

irradiated. A map of Cape Canaveral showing instrumentation site locations and average effective radiation powers is included."

42. R. N. Skeeters, S. Shefler, Shielding Device Against RF Energy for Zuni Rocket Motor MK 16 Mod 0, Naval Ordnance Test Station, China Lake, Calif., NAVWEPS Rpt. No. 7747, Aug. 1961, (AD-261 541).

"This report describes a shielding device used to protect the ignition terminal of the Zuni Rocket Motor MK 16 Mod 0 from contact with sources of current and from the effects of electromagnetic fields that otherwise might induce current in the ignition circuit and possibly cause premature ignition. The theory of shielding as a protection against radio frequency (RF) fields is reviewed, and instrumentation for detecting RF energy in the ignition circuit is described."

FUEL HAZARDS

43. F. J. Woods, K. G. Williams, et al, Shipboard Studies of Fuel--Vapor Ignition by Radio Arcs, Naval Research Lab., Rpt. No. 5443, Jan. 25, 1960, (PB 143 950).

44. V. T. Burkett, I. W. Wolf, Z. Zenon, Study of the Radio Frequency Radiation Arcing Hazard in Refueling, General Electric, Tech. Rpt. No. RADC-TR-56-68, Feb. 1956, (AD-93 088).

This report was prepared to enable the U. S. Air Force to determine the order of magnitude of hazards of refueling aircraft in the vicinity of high-powered radar. Blanking and shielding of the radar beam in the direction of the refueling areas is discussed as possible ways of eliminating the hazards. Laboratory and field tests which were used to determine the arcing hazards are discussed.

CHAPTER X

SHIELDING

INTRODUCTION

There is no one solution for all RFI problems. However one of the most common methods of eliminating, or at least minimizing RFI is through the application of an electromagnetic shield. A shield is any device which is used to decrease the amplitude (intensity) of an electromagnetic wave in a region as compared with its amplitude in the regions outside the shield. There are two broad aspects of shielding; one, interference can be shielded at its source, and two, shielding can be used to provide a comparatively small region which is interference-free. Shielding effectiveness is dependent upon many factors including the material of which a shield is constructed, the type wave to be shielded, and the frequency of the wavefield.

THEORY OF SHIELDING

The most commonly referenced work on the theory of shielding is S. A. Schelkunoff's book, "Electromagnetic Waves", ref. (2). Schelkunoff treats shielding as a transmission line problem. This approach is demonstrated in Fig. X - 1. An electromagnetic wave, W_0, is traveling through region 0 when it strikes boundary "a" of the shield. Because of the difference in intrinsic impedance of the two regions, part of the wave, W_0', is reflected, and part of

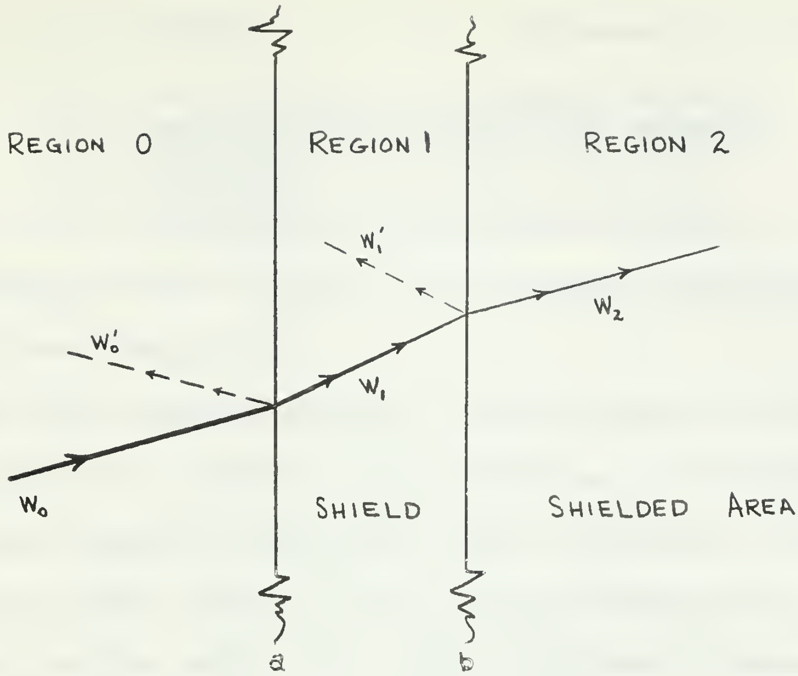

Figure X - 1   Reflection and Attenuation of Wave Striking Shield

the wave, W_1 is transmitted. As W_1 travels through region 1, it is attenuated. When W_1 strikes the boundary "b" there is reflection of W_1' because of the difference in intrinsic impedance between regions 1 and 2. W_2 is that portion of W_1 which is transmitted to region 2. Thus, the total shielding effect is made up of a reflection factor and an attenuation factor. The "shielding efficiency" in db is 20 $\log_{10} \frac{W_0}{W_2}$.

Schelkunoff develops the following equation for shielding efficiency, S, of metallic shields:

$$S = R + A + 20 \log_{10} \left| 1 - \frac{(k-1)^2}{(k+1)^2} e^{-\sigma t} \right| \text{ db}$$

where

$$R = 20 \log_{10} \frac{|k+1|^2}{4|k|} \text{ db} \quad \text{(reflection factor)}$$

$$k = \frac{\text{intrinsic impedance of metallic shield}}{\text{intrinsic impedance of incident wave}}$$

$$A = 8.686\sqrt{\pi \mu f g}\quad t \quad \text{db} \quad \text{(attenuation factor)}$$

μ = permeability of shielding material
g = conductivity of shielding material
t = thickness of shielding material
f = frequency
σ = the complex propagation constant

The last term in the equation for S becomes significant only when A is less than 10 db.

From this equation several important conclusions can be drawn: first, the greater the difference in intrinsic impedances in two regions, the greater the reflection, and second, attenuation losses will be small at low frequencies.

In an earlier work, ref. (3), Schelkunoff presents detailed solutions of special applications of shielding to cylindrical waves, spherical waves, and plane waves at oblique angles.

A. R. Kall and I. Zipper include a review of Schelkunoff's equations and discuss the theory behind them in ref. (4). This report shows how constant attention to shielding principles must be made through the design, construction, and maintenance phases of a shielded structure.

In a paper titled "Shielding Efficiency Calculations for Screening, Waveguide Ventilation Panels, and Other Perforated Electromagnetic Shields", ref. (5), William Jarva adds correction factors to Schelkunoff's equations to calculate the shielding effectiveness of non-solid shields. Calculations were made and laboratory tests were performed in the frequency range of 0.1 to 100 mc. Comparisons showed

only minor variations in shielding efficiencies between theoretical and experimental values.

CHOICE OF SHIELDING MATERIALS

Normally reflection is disregarded in shielding design because the reflection factor is almost negligible at higher frequencies. Therefore for rough calculations, Schelkunoff's equation has been reduced to

$$S = A = 3.338\ t\sqrt{f_m \mu_r g_r} \quad \text{db}$$

where t = thickness in mils
f_m = frequency in megacycles
μ_r = relative permeability
g_r = conductivity relative to copper

This equation was found in several references, for example refs. (23) and (36). It would appear desirable to have a material which has a high permeability and high conductivity, however it is found that most of the good conductors have a relative permeability of one and most magnetic materials which have high permeability are poorer conductors. Another factor, which is not apparent from the equation, is that the permeability of magnetic materials varies with saturation and frequency. At higher frequencies μ_r for a magnetic material may decrease to a value of one.

In ref. (10) N. H. Cale presents a table giving a comparison of the shielding effectiveness of seven different materials over a frequency range of 500 kc to 10,000 mc. These measurements were taken in accordance with the test procedures outlined in MIL-STD-285 and are in the table presented in Fig. X - 2.

Frequency		Galv. Steel 22ga.	Al. Sheet 0.026in.	Cu. Mesh No.22	Electro-Sheet Copper 1-oz.	Electro-Sheet Copper 4-oz.	Electro-Sheet Copper 7-oz.	Copper Sheet ETP 16-oz.
500 kc	a	75	71	66	75	65	73	66
1000 kc	a	80	80	71	70	71	68	72
0.15 mc	b	100	100	100	100	100	100	100
0.50 mc	b	100	100	100	100	100	100	100
1.5 mc	b	100	100	100	100	100	100	100
5.0 mc	b	100	100	100	100	100	78	53
10 mc	b	100	100	100	100	100	100	78
60 mc	b	87	76	70	87	77	78	73
100 mc	b	77	69	48	74	64	69	54
400 mc	c	42	61	64	59	57	54	70
750 mc	c	55	54	64	73	61	57	61
1000 mc	c	42	49	62	81	68	61	66
5000 mc	c	30	23	32	29	39	32	55
10000 mc	c	20	9	13	22	28	18	5

a. Low Z magnetic range
b. High Z electric field
c. Plane wave range

Fig. X - 2 Comparative Data on Commonly Used RFI Shielding Materials (Attenuation in Decibels)

Many studies have been made to find new materials to use in shielding applications. One reason for such studies is the relative high cost of good shielding materials such as copper; another reason is that such metals are usually very scarce in times of national emergency. The results of one such study are presented in ref. (15). Twenty-four different materials, including aluminum foil in combination with fiberglas or mylar, conductive glass yarn, semi-conductive plastic, aluminum tape, tinned copper braid, conductive polyethylene, collodial graphite, and silver, were used as cable shields and compared with RG 58/U coaxial cable. It was found that a shield made up of eight carriers of

conductive glass yarn plus eight carriers of copper was almost as effective as the standard. A savings in weight was also realized.

The Naval Research Laboratory has conducted several experiments to determine the shielding effectiveness of coke. These experiments are described in refs. (11) and (25). A project in which a wooden hut was completely surrounded by a two foot thickness of coke is described in ref. (11). This construction offered at least 75 db of isolation. The author points out that many construction problems would be encountered in an attempt to shield an entire building with coke. He also states that the weatherability of coke is uncertain.

Conductive glass is another material that has been studied as a possible shielding material. In ref. (14) H. M. Sachs, et al, report on one study of the shielding effectiveness of conductive glass used in fluorescent light shielding applications. They found that the efficiency of light transmission was reduced approximately 10 percent when a conductive coating was applied to the glass under study. They also found that the conductive glass would shield the radiated noise output of a fluorescent light to within the limits established by Military Specification MIL-I-16910A. They also found that shielding effectiveness increases as the resistance of the applied coating decreases.

SHIELDED ENCLOSURES

Shielded enclosures (or rooms) can basically be divided into three categories: single-shielded, double-shielded, and cell-type. The first two categories are the types which are most often used when a shielded enclosure is constructed as an integral part of a building. The cell-type enclosures are particularly adaptable to demountable and portable type shielded rooms although they are not always used in this manner. A single-shielded enclosure consists of one layer of conducting material completely surrounding the enclosed space, whereas a double-shielded enclosure has two layers of conductive material, normally separated by one to six inches and connected electrically at only one point if possible. The cell-type enclosure also has two layers of conductive material but the enclosure is made up of panels, each panel being a "cell" or completely enclosed unit. The surrounding conductive layer may be either in solid sheet form or may be woven into the form of a screen.

Most factors that degrade the shielding effectiveness of a shielded enclosure are common to all three types of enclosures. The first degrading factor to be considered is that of faults and discontinuities in the conductive layer. (In the following discussion it is assumed the shielded enclosure is designed to <u>keep</u> <u>out</u> RFI.) If the enclosure is to act as a shield, the current flow due to electromagnetic fields must be restricted to the outside of the enclosure.

Any small discontinuity, such as poorly sealed access doors or ventilating duct or joints between conductive sheets, will allow currents to enter the enclosure and establish fields within the enclosure. This type problem is more severe with cell-type construction and it has been found that the joints between adjoining panels must be tightened periodically if the shielding effectiveness of such an enclosure is to be maintained.

Another defect which lowers the shielding effectiveness of an enclosure is the passage of a conductive material through the shield of the enclosure when there is not a zero impedance bond between the conductive material and the shield. A nail driven through the shield or an improperly installed water pipe is an example of such a defect, and either may act as an antenna to pick up fields external to the enclosure and reradiate them inside the shielded enclosure if they are not properly bonded to the shielding.

An unfiltered power line can also degrade the shielding effectiveness of an enclosure. The answer to this problem is the insertion of low pass filters in the power line just prior to entry of the line into the enclosure.

When a solid sheet conductive material is used as the cover over the shielding enclosure it is necessary to provide some method of ventilating the enclosure. Screening could be used but it has been found that screen in general is not as satisfactory a shield as solid metal Therefore

use is made of a group of parallel waveguides of such size that the cutoff frequency is much higher than the frequencies which are to be excluded. Refs. (5), (21) and (36) present formulas which may be used to determine the sizes of the waveguides. For rough calculations, the formulas in ref. (36) are easiest to use. For a circular guide the diameter is found by

$$d = \frac{6820}{f} \text{ inches}$$

f = lowest frequency (in mc) to be transmitted

The amount of air required for ventilation is established and the area, A, necessary for passage of this air is determined. Then the number of parallel guides required is determined by $N = \frac{A}{a}$ where a is the cross sectional area of each guide. Because each section transmits a certain amount of energy the attenuation offered by N parallel sections is less than that offered by each section. The reduction in attenuation is given by $db = 20 \log_{10} N$. The attenuation, in db, of one section of circular guide is given by

$$a_{\ell} = \frac{32\ell}{d} \text{ db}$$

where ℓ = length
d = diameter
ℓ and d being in the same units

Then the required length

$$\ell = \frac{d\ (a + 20\log_{10} N)}{32}$$

The author states, that as a factor of safety, the actual length used should be 25 percent greater than that calculated.

Lighting may be another problem area in a shielded enclosure. Since fluorescent lights are a source of RFI they should not be used unless they are shielded. Incandescent type lighting is normally interference free.

The physical size of realizable shielded enclosures has grown immensely in recent years. Refs. (29), (36) and (52) are reports on some of the larger shielded enclosures which have recently been publicized. The use of larger sized shielded enclosures has also given added impetus to studies of the use of less expensive shielding materials. Ref. (56) reports the use of 24 gauge TRAN-COR-72 sheet steel in the construction of a shielded room. It was found that an attenuation of 46 db was attained at 15 kc and an attenuation of more than 160 db was attained between one and ten mc.

SHIELDED CABLES

Shielding of cables is important because cables may radiate interference to surrounding circuits and they are also susceptible to picking up interference from other sources. Shielding against electric fields may be effected by enclosing the conductors in a highly conductive enclosure, whereas a magnetic material is required for shielding against magnetic fields. Electrical conduit may, in itself, act as a shield, but it has the major disadvantage of not being flexible. In ref. (60) S. L. Shive presents results that were obtained in measuring the shielding effectiveness of several samples of flexible and non-flexible shields. These results

are presented in Fig. X - 3. The curves are taken from several figures in ref. (60). Double shielded cable is also available if single shielding is not effective enough.

In ref. (56) Arnold L. Albin suggests some general rules to be followed in reducing interference in cables. In general, he states that power cables, high level and low level signal cables should be physically isolated from each other as much as possible, all r-f signal cables should be shielded, proper grounding of shields must be applied, and twisted shielded pairs may be necessary if magnetic fields are present.

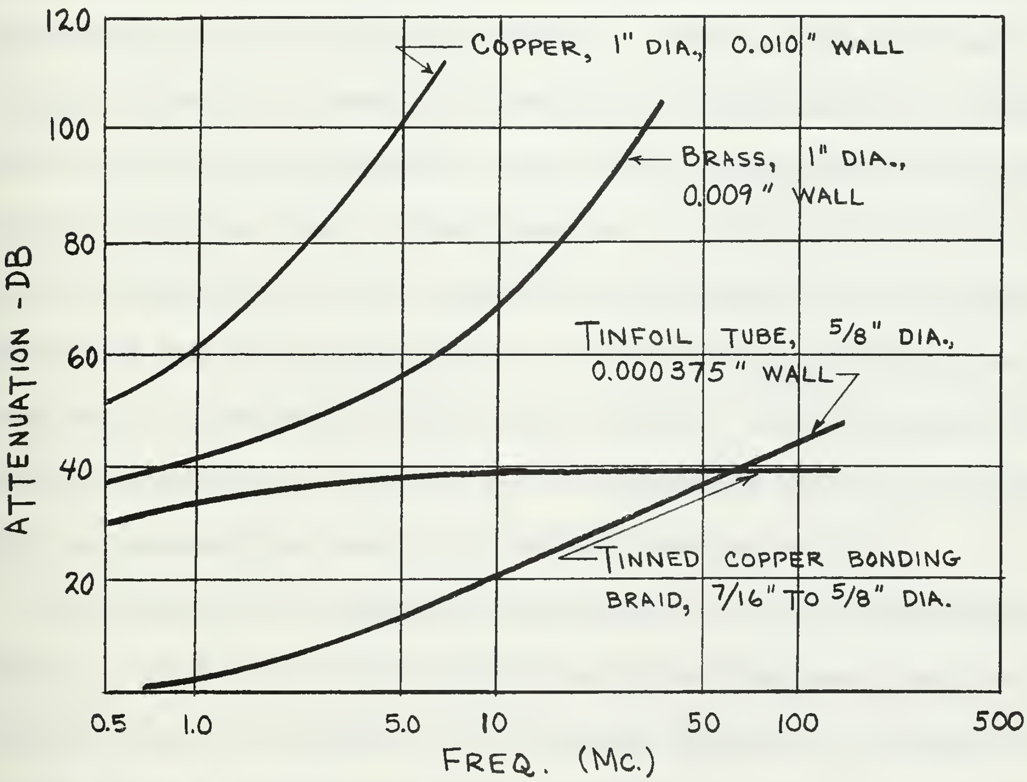

Fig. X - 3 Shielding Effectiveness of Various Cable Shields

GROUNDING, BONDING, AND GASKETING

Just as proper grounding can eliminate some RFI sources, improper grounding can worsen RFI problems. A short length of conductor that offers a low impedance to ground for d.c. and low frequency a.c. may present a very high impedance to ground for high frequencies, especially when its length is an odd multiple of quarter wavelengths. It is normally advisable to provide a separate ground system for both signal and power circuits. Long ground leads should also be avoided.

In ref. (81) Irwin M. Newman and Arnold L. Albin report the results of tests performed to determine the proper grounding techniques on shielded cables. They concluded that shields should be bonded to ground at both ends of a coaxial cable to minimize coupling when radio frequencies are used. However for low level, low frequency applications, they recommend grounding of the shield at only one end to prevent 400 cycle and 60 cycle ground currents from inducing audio frequency interference into the cables. If the radio frequency interference under this arrangement is not tolerable they recommend the use of shielded twisted pairs.

Grounding of a shielded enclosure is not considered necessary. In fact if the shielding effectiveness changes with the addition or deletion of a ground there is a strong possibility that a shielding defect exists.

The purpose of bonding is to form a low impedance path

between any two metallic structures which may be in an electromagnetic field. When two structures are isolated from each other even a small amount of charge accumulated on the structures may cause a large potential difference. This may cause an arc or spark discharge, one of the most serious sources of RFI. If the two structures are bonded together there is less chance of the impedance between them changing due to mechanical vibration or shock. Thus bonding will eliminate the generation of RFI caused by a varying impedance.

In general there are two main types of bonding: direct bonding and bonding by jumpers. Direct bonding is preferable and is achieved by ensuring permanent metal-to-metal contact between the members to be bonded. Extreme caution must be used in jumper bonding at high frequencies because of the fact that the high frequency impedance of a jumper may be appreciably greater than its low frequency or d.c. impedance. The difference in these two impedances is due to the series inductance and the distributed capacitance of the jumper and the capacitance of the bonded members.

Gasketing materials have found wide usage when it is necessary to have removable panels on a shielded enclosure. The one common property of nearly all conductive gasketing materials is that they must have some degree of compressibility in order that they may conform to the two mating surfaces. Ref. (80) describes some of the common types of r-f

gasketing materials and lists some of the advantages and disadvantages of each type. Some of the common types are silver-plated copper braid interwoven with textile fibers over a neoprene core, neoprene impregnated aluminum mesh, serrated finger-type, saw-tooth seams, aluminum tubing filled with neoprene, and compressed knitted wire mesh.

SHIELDING MEASUREMENTS

Numerous methods have been proposed for measuring the shielding effectiveness of materials used in shielded cables and enclosures. In ref. (104) H. E. Dinger and J. E. Raudenbush proposed a technique by which small samples of materials could be tested in both high- and low-impedance fields. The samples were inserted between two shield cans containing small transmitting and receiving elements and the attenuation of the sample was determined by a ratio of the energies reaching the receiving element with and without the inserted sample. This method was limited to an upper frequency of 100 mc because of the physical dimensions of the transmitting and receiving elements.

The same authors, in ref. (97), describe three other methods of evaluating shielding room effectiveness. The first of these is referred to as the "door-open, door-closed" method. This method consists of placing a transmitter outside a shielded enclosure and measuring field intensity at the center of the room with the door open and then with the door closed. The attenuation of the enclosure is the ratio

of the two readings expressed in decibels. This normally gives a conservative result. The second method is the "inside, outside" method. It differs from the previous method in that the initial reading is taken outside the enclosure but as close as possible to it. It is assumed that the field surrounding the room will have a high gradient. The third method, termed the "uniform-field" method, consisted of transporting the shielded enclosure to the vicinity of a ten to 300 kw transmitter antenna system. The enclosure was positioned in a uniform field and field intensity readings were taken inside and outside. The major disadvantage of this method was the necessity of finding transmitters that varied over a wide enough frequency range.

The most important method of measuring shielding attenuation for individuals contracting with the Department of Defense is described in MIL-STD-285. This standard covers the frequency range from 100 kc to 10,000 mc and includes procedures for measuring attenuation of low- and high-impedance and plane wave fields. Types of equipment, equipment spacing and orientation, and specific frequencies are set down for the measurements. Sources of intense peak power magnetic and electric fields are also given.

Although several references ((90), (91), (94), (102)) were found relating to development of shielding effectiveness tests for cables, no military standard could be found.

CHAPTER X
BIBLIOGRAPHY AND ABSTRACTS

THEORY

1. John P. Quine, Howard Q. Tolten and others, Electromagnetic Shielding Principles. Vol. 1, Rensselaer Polytechnic Institute, March 1, 1956, (AD-91 297).

2. S. A. Schelkunoff, Electromagnetic Waves, D. Van Nostrand Inc., New York, 1943.

   This is a general book on electromagnetics and includes chapters on the fundamental electromagnetic equations, networks, transmission theory, waveguides, radiation and diffraction, and antenna theory. Sections which are most pertinent to the topic of shielding are 4.9, 7.13, 7.19, 8.18, and 8.19.

3. S. A. Schelkunoff, Impedance Concept and Its Application to Problems of Reflection, Refraction, Shielding and Power Absorption, BELL SYSTEM TECHNICAL JOURNAL, Vol. 17, Pp. 17-48, June 1938.

   This paper attacks the theory of shielding from the transmission line theory approach, i.e., whenever an electromagnetic wave passes through a transmitting medium, there is an absorption loss and whenever it passes from one medium to another of different impedance, there is a reflection loss. Special applications of these concepts are treated for cylindrical waves, spherical waves, and plane waves with an oblique angle of incidence. The method of images is also presented.

4. A. R. Kall, I. Zipper, RFI Shielding and Suppression, Electro-Search, Inc., May 22, 1952, (AD-73 630).

   This report covers work done under Contract No$_y$-18640 with BUDOCKS for preparation of plans and specifications, consulting services, inspection, and testing of RFI portions of construction of (1) the human centrifuge project at the Aviation Medical Acceleration Laboratory, Naval Air Development Center, Johnsville, Pa., and (2) the Electronics Standards Laboratory, Naval Air Station, Norfolk, Va. RFI suppression techniques were designed into the buildings. Material covered includes grounding systems, RFI suppression theory, RFI measurements on equipment and buildings, and maintenance and inspection techniques.

5. William Jarva, Shielding Efficiency Calculations for Screening, Waveguide Ventilation Panels, and Other Perforated Electromagnetic Shields, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 478-498, Nov. 1961, (AD-276 205).

"The basic procedures for calculating the shielding efficiency of continuous metallic shields, which were originally developed by S. A. Schelkunoff, have been found to apply equally as well to perforated shields. Methods are developed for calculating the shielding to be expected from discontinuous shields having a wide range of different physical structures, and results are compared with values measured in the laboratory. Theoretical explanations are provided for test results obtained by some investigators, which are essentially independent of frequency, whereas results obtained by others vary radically with frequency..."

6. J. P. Quine, Theoretical Formulas for Calculating the Shielding Effectiveness of Perforated Sheets and Wire Mesh Screen, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 315-329, Feb. 1957, (AD-234 211).

Formulas are derived for calculating the high and low impedance attenuations obtained when an aperture in an equipment cabinet is covered with perforated conducting sheets or wire mesh. The formulas are based on aperture polarizability concepts first introduced by H. A. Bethe. For infinitely thin sheets, attenuation is proportional to the first power of the aperature linear dimension. For finite sheet thicknesses, each perforation is treated as a cutoff waveguide. Calculated and measured values are compared.

7. D. B. Wright, C. R. Freberg, Theoretical Investigation of Electromagnetic Shielding, Naval Civil Engineering Laboratory, Report No. TR 006, Nov. 1949, (PB 107 404).

MATERIALS

8. F. O. McMillan, Asphalt Emulsion Treatment Prevents Radio Interference, ELECTRIC WEST, Vol. 74, pp. 16-19, June 1935.

9. A. P. Efimov, Choice of Material for Electromagnetic Shielding of Premises, RADIO ENGINEERING, Vol. 13, pp.80-89, 1958.

10. N. H. Cale, A Comparison of R-F Shielding Materials, ELECTRONIC INDUSTRIES, Vol. 21, pg. 106, Dec. 1962.

Using the test procedures as given in MIL-STD-285 the comparative shielding effectiveness of seven commonly used materials was measured. A table is given showing the db attenuation at 14 frequencies ranging from 500 kc to 10,000 mc.

11. P. F. Nicholson, Electromagnetic Shielding with Coke, Naval Research Laboratory, Memorandum Report 1080, July 18, 1960.

This report describes a field test and laboratory tests performed on coke to determine its effectiveness as an e-m shield. The field test involved complete envelopment of a small wood hut in a two-foot blanket of coke. At least 75 db of shielding was afforded in the HF and VHF portions of the spectrum. Laboratory tests lead to the conclusions that the shielding effectiveness was dependent upon (1) the thickness of the coke layer, (2) the size of the individual pieces of coke, and (3) the purity of the coke. The author also raises some practical problems that would be involved in surrounding an entire building with coke.

12. E-M Shielding with Transparent Coated Glass, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS. Vol. 42, pp. 548-553, March 1954.

13. R. J. Fabian, Engineer's Guide to Electrical Material, MATERIALS IN DESIGN ENGINEERING, Vol. 55, pp. 121-132, June 1962.

This article covers all types of materials including conductor, maser, magnetic, emitter, and shielding. Nickel alloys, notable mumetal, are recommended for electric shielding. 50% nickel - 50% iron alloys, silicon iron, or soft cold rolled steel coated with ferrite powders are recommended for magnetic shielding. A sandwich of nickel alloy and copper is also recommended.

14. H. M. Sachs, H. G. Tobin, W. Benjamin, Evaluation of Conductive Glass in Fluorescent Light Shielding Applications, Proceedings of the 6th Conference of Radio Interference Reduction, Armour Research Foundation, pp. 281-294, Oct. 1960, (AD-253 015).

Comparisons are made of the shielding properties of conductive glass of various resistance coatings to

that of copper screening, hardware cloth, and an aluminum grill as used in a fluorescent lighting fixture. The effect of coated glass on light transmission is also discussed. The grounding requirement for coated glass shields is also considered.

15. Evaluation of Shielding Materials for Aircraft Wire and Cable, American Enka Corp., Willimantic, Conn., Final Rpt., Aug. 21, 1961, (AD-261 499L).

"A total of 24 materials, singly and in various combinations, were evaluated to determine the shielding effectiveness of each as compared to the Cu braid described in MIL-C-7078A specification. Measurements were made over the frequency range of 150 kc to 140 mc in maximum increments of one octave. Several constructions equalled or exceeded Cu at the high end of the frequency range (10 to 140 mc) when tested for the transverse-electric mode and none were the equal of Cu when testing for the transverse-magnetic mode (150 kc to 2.4 mc). The material which came the closest to matching on all Cu braid for shielding effectiveness was one in which eight carriers of conductive glass yarn were substituted for eight carriers of Cu."

16. E. Hawthorne, D. B. Geselowitz, Investigation of the Shielding Properties of Conducting Glass, Moore School of Electrical Engineering, Oct. 1953, (AD-23 015).

Both theoretical and experimental determinations were made of the shielding effectiveness of conductive-coated glass. Some possible applications that were evaluated were (1) multiple layers of conductive-coated glass, (2) single layers of coated glass, and (3) coated glass covers for apertures in metallic shields. The loss in translucency is also investigated.

17. S. Oster, Linear and Non-Linear Resistive Materials for the Reduction of Radio Interference, Material Laboratory Naval Shipyard. New York, N. Y., Dec. 1956, (AD-139 997).

18. Oakes, Magnetic Shielding by Super Conducting Films, JOURNAL OF APPLIED PHYSICS, Vol. 33, pp. 177-179, Jan. 1962.

19. Ralph E. Shepherd, Measurements of Electromagnetic Wave Attenuation Characteristics of Portable Shelters Composed of Pliable Reflecting Materials, Pickard and Burns, Inc., Needham, Mass, April 15, 1959, (AD-234 762).

"A model portable shelter was analyzed under 3 different operational conditions: (1) the batting and ground cloth carefully joined to avoid openings; (2) the batting readjusted and the ground cloth removed: and (3) the frame attached to the ground leads at each corner (less ground cloth). The results for the condition with ground cloth in place show a degree of attenuation which, with moderate adjustments should result in a shelter with adequate shielding or attenuation to fully protect personnel and/or equipment as required. For the 1,000 mc situation, as an example, the degree of attenuation achieved is at least equal to that of certain all-metal shelters available commercially. Despite the high degree of attenuation achieved, internal leakages were detected at the following regions: (1) the center seam (gaps due to type of construction and fastening); (2) area near joints of ground cloth and underlapped sides of shelter (no electrical bonding provided); and (3) zippered entrance (cloth parts of zipper acting like a slot antenna) causing coupling of external energy to interior of shelter. The use of a conducting ground cloth, which provides an average of 30 db attenuation up to 10,000 mc, is shown to be essential. The failure of the shelter to attenuate evenly and effectively over all areas studied was not due to poor selection of reflective material, but rather to a need to re-arrange the material to achieve complete electrical contact at all points."

20. B. H. Porter, Non-Metal Shields; Collodial Graphite Films, ELECTRONICS, Vol. 15, pg. 33, April 1942.

    This article deals with the application of films of collodial graphite on glass, plastic, and wood to form shields for vacuum tubes, electronic musical instruments, electrostatic generators, and guard rings for vacuum apparatus.

21. D. J. Angelakos, Radio Frequency Shielding Properties of Metal Honeycomb Materials and of Wire-Mesh Enclosures, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 265-280, Oct. 1960, (AD-253 015).

    In this paper the cells of honeycomb materials are treated as waveguides and a method is presented whereby the upper frequency at which the material acts as a shield may be estimated. The low frequency limit is determined by considering the structure as having an equivalent mass or an equivalent

conductivity. The calculation of the shielding provided by wire-mesh is based on the Rayleigh formula for diffraction of plane waves by a small circular aperture and extension of this concept to small square apertures. The losses within the mesh are also taken into account.

22. N. R. Zitron, Shielding By A Thin Conducting Sheet Against Transient Electromagnetic Signals, Cruft Laboratory, Harvard Univ., Cambridge, Mass., Techn Rpt. No. 311, Aug. 10, 1959, (AD-235 694), (Also published in JOURNAL OF RESEARCH OF THE NATIONAL BUREAU OF STANDARDS, Vol. 64D, pp. 563-567, Sept. 1960).

"The shielding effect of a thin, horizontal imperfectly conducting sheet against the transient field of a vertical magnetic dipole when excited by a ramp function is investigated. The results are calculated by taking Laplace transforms of the frequency spectrum functions for the steady-state problem. The response to the ramp function is calculated and the significance of the results in shielding against surges is discussed."

23. J. F. Sodaro, Shielding Nomograph, ELECTRONICS, Vol. 27, pg. 190, May 1954.

"Attenuation chart simplifies design calculations for shielded rooms, filter enclosures, coaxial cables, and chassis construction materials. Effectiveness of shielding can be determined for both magnetic and nonmagnetic materials."
The nomograph is made up in terms of frequency, resistivity, magnetic permeability and attenuation. In addition the resistivity and permeability for nickel, cast iron, low-, medium-, and high-silicon steel, permalloy, mumetal, aluminum, brass, copper, bronze, tin and zinc are given.

24. E. L. Hill, The Shielding of Radio Waves by Conductive Coatings, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS, ANTENNAS AND PROPAGATION--AP-3, No. 2, pp. 72-76, April 1955.

"A theory is given of the shielding of radio waves by the conducting coatings which are placed over the cockpit dome and windows of an airplane. At low and medium frequencies the shielding arises primarily from the quasi-electrostatic charges which are induced on the surface, the effects of which increase strongly with decreasing frequency. At higher frequencies the shielding from this

source diminished in importance while that from the induced eddy currents increases in effectiveness."

25. P. F. Nicholson, Study of Coke-Aggregate Concrete As A Shield to Electromagnetic Radiation, Naval Research Lab., Washington, D. C., NRL Rpt. No. 5473, May 6, 1960, (AD-238 302).

"The electromagnetic behavior of a coke-aggregate concrete as a shield to radiation has been investigated. Measurements have been taken on a sample within the frequency range from 1 to 1000 Mc. The loss-versus-frequency characteristic can be predicted with reasonable accuracy by the adaptation of classical propagation theory to the transmission of electromagnetic waves through an imperfect conductor. With a knowledge of the approximate value of complex permittivity and a measurement of direct-current conductivity, substitution of these parameters into a general equation will then yield the total insertion loss at the desired frequency."

SHIELDED ENCLOSURES

26. William D. Murray, Alan M. Nathan, Harold Gussaroff, Air Transportable Shelter for Ground Electronic Equipment, New York Univ., College of Engineering, Contract AF 30 (602)205, Tech. Rpt. 222.05, May 15, 1954, (Ad-43 896).

27. C. C. Pine, Construction of Shielded Room in VHF Shield, ELECTRONICS, Vol. 21, pg. 150, April 1948.

This article describes a triple shielded room, the outer shield of $\frac{1}{4}$-inch galvanized mesh, the middle shield of graphite-impregnated cloth, and the inner shield of copper foil. Power line filtering and ventilation features are described.

28. Copper-Lined Room at G E Plant Excludes Electromagnetic Wave, IRON AGE, Vol. 173, pg. 150, May 13, 1954.

The construction of a room 68' X 58' X 60' high is reported. 20,900 lbs of copper was used for shielding the room--an anechoic chamber for the G. E. sound test building. Specifications call for at least 100 to 1 attenuation at 1 mc.

29. C. C. Eaglesfield, Design of a Screened Room, ELECTRONIC ENGINEERING, Vol. 18, pp. 106-108, April 1946.

30. Design of a Welded Steel Shielded Room, Naval Civil Engineering Lab., M-046, Sept. 1951.

31. Arnold L. Albin, Designing Noise-Free Enclosure Openings, ELECTRONICS, Vol. 31, pg. 48, Aug. 29, 1958.

"Technique reduces interference introduced by meter ventilation openings in electronic equipment enclosures. When apertures are designed as waveguide attenuators operating below cut-off for lowest propagating frequencies, shielding efficiencies up to 100 db are obtained."
The author uses the formula

where r = radius
f = frequency

to determine attenuation of the TE_{11} mode, which is dominant in circular waveguides. A chart is given for determining attenuation in rectangular waveguides.

32. Frank J. Rizzo, Alvin O. Ramsley, Frank O. Johnson, Development of Electromagnetically Shielded Portable Shelters, Quartermaster Research and Engineering Command, Natick, Mass., Oct. 1959, (AD-231 509).

"The various steps in the development of a design for portable shelters which afford shielding from microwave radiation are described. The shelters were designed to house electronic computing devices and operating personnel in proximity to radar transmitters. Shielding from microwave radiation is necessary to prevent interference and consequent malfunction of electronic equipment and to insure safety to operating personnel. Reflectivity to microwave radiation was measured for several flexible materials. A silverized nylon fabric and aluminized polyester film were found to be more effective in reflecting the energy than the other materials studied. A scale model of the shelters was constructed of materials suggested for use in the final design. The model was submitted for evaluation to a field type test to determine levels of attenuation within the shelters when illuminated with microwave radiation at three frequencies. It was found that leakage at overlapping joints limited attenuation to an average of about 40 db for 'L' band, 33 db for 'S' band, and 26 db for 'X' band. Designs are suggested for improving the closure at overlapping

joints which should raise the level of attenuation."

33. Donald L. Benedict, Elimination of Radio Interference by Shielding and Design of Shielded Rooms, Stanford Research Institute, SRI Project 336, Aug. 1952, (PB-114 646), (TIP G U24859).

An experimental room was made of 0.635-mm silicon transformer steel sheet and evaluated. Forty-six db attenuation was attained at 15 kc. The attenuation was proportional to the square root of the frequency and became greater than 160 db in the 1 to 10 mc range. Construction procedures and test procedures are described along with auxiliary facilities such as lighting, ventilating, and power line filtering.

34. William C. Weber, Investigation of a Screen Room to Suppress Interference from Arc Welders, Engineering Development Laboratory, Naval Air Development Center, Johnsville, Pa., Rpt. on Phase 1, Rpt. No. NADC ED-6014, July 18, 1960, (AD-241 829L).

"This report covers an investigation to determine the effectiveness of a screened enclosure to suppress the high-frequency interference, both conducted and radiated, generated by arc welders. The P & H Model DAR-300 HF-SG a.c./d.c. welder and the Miller Model BWC-300 a.c. welder were used in a modified screened enclosure. Both welders, when operating as a.c. welders, produce conducted and radiated interference above the limits of specification MIL-I-16910 (Ships). The screen room shields the high-frequency radiation from both welders to within the limits of this specification, and the filters on the powerline to the screen room eliminate all conducted interference. Tests indicate that no interference is produced by the P & H welder during d.c. welding. It is recommended that a study be conducted to determine if any new method can be found for the shielding of radiated interference from a.c. arc welders."

35. R. J. Costello, B. D. McMichael, Large Shielded Enclosures, ELECTRONICS, Vol. 30, pg. 236, Aug. 1, 1957.

This article reports that a large shielded room, 40 ft. long by 35 ft. wide by 18 ft. high, has been constructed to accommodate complete aircraft and missile systems. Hydraulic and electric power are made available. The room is constructed of

galvannealed iron panels bolted on steel channels and tensioners.

36. Gustavus A. Morgan. Jr., Notes on Design, Construction, and Evaluation of Shielded Rooms, Naval Research Lab., Rpt. No. 3578, Dec. 9, 1949, (ATI 72 964).

The basic principles of shielding are viewed with particular attention on how these principles are applied to shielded rooms. Line filtering, ventilating openings, grounding, and the effects of defects are reviewed. Several methods of evaluating the shielding performance of a room are given.

37. Optimum Shielding of Equipment Enclosures, ELECTRONIC DESIGN, pg. 48, Feb. 3, 1960.

38. J. Miedzinski, S. F. Pearce, The Performance of Screening Rooms, ELECTRONIC ENGINEERING, Vol. 22, pp. 414-419, Oct. 1950.

Four types of screened rooms were tested: (1) perforated zinc sheet, (2) electro-galvanized expanded steel, (3) tinned iron mesh, (4) galvanized iron wire netting. In general, the type (1) room gave the highest attenuation over the frequency range used-- .75 to 25 mc. The transmitter was placed inside the screen rooms and measurements taken outside. A theoretical analysis is also made.

39. Harry W. Kenny, Barton L. Conard, A Practical Approach to R-F Shielded Enclosure Design, Ace Engineering and Machine Co., presented at the Armour Research Foundation, Dec. 12, 1961.

The factors involved in construction of a shielded enclosure are described in the layman's language. The importance of shield continuity and power line filtering are discussed. This report would make a good introduction to R-F shielding practices for an architect designing a structure which included shielded areas.

40. C. S. Vasaka, Preliminary Service Manual for NADC-AEEL Takedown Cell Type Screen Room, Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-54122, Dec. 1959, (AD-55 214).

This manual describes the cell-type screen room which was designed by NADC and also gives maintenance procedures which are applicable to most shielded rooms of similar construction. Test

procedures for locating leaks are also given.

41. Edward M. T. Jones, Principles Governing the Construction of Shielded Rooms, Stanford Research Institute, SRI Proj. No. 336, Tech. Rpt. 1, April 1951, (PB 114 742), (TIP G U18108).

An analysis is presented of methods of obtaining a shielded enclosure that will provide 120 db attenuation to all e-m signals in the range from 15 kc to 24,000 mc. The shielding problem is described in terms of transmission line theory. Specific recommendations are given for the construction of shielded rooms. Power line filters are also discussed.

42. A. G. Swan, Radiation from R-F Heating Generators, ELECTRONICS, Vol. 19, pg. 162, May 1946.

A simple description of shielded room construction and line filtering is given for preventing radiation from diathermy equipment used in Hawaii during World War II.

43. Donald L. Benedict, Radio Interference Elimination, Stanford Research Institute, Calif., Progress Rpt. No. 2, March 30, 1951, (AD-222 178).

"Methods of eliminating radio interference are investigated. The project.....includes studies of the nature of interference from various sources, methods of measuring the interference and noise power level, filter networks for suppression of interference at its source, and shielding procedures using conductors or lossy dielectric materials..."

Donald L. Benedict, Radio Interference Elimination, Stanford Research Institute, Calif. Progress Rpt. No. 3, June 15, 1951, (AD-222 177).

"The properties of various sheet iron stocks have been examined. Armco Transformer Steel Type M-19 or M-27 is used. A shielded room is to be designed which will feature good attenuation, low cost, and freedom from such difficult construction procedures as wooden frames and double shields. A room so designed will be expendable; thus, special assembly bolts and storing difficulties, including warpage and shrinkage, which are anticipated in the now popular demountable rooms, will be eliminated."

Donald L. Benedict, Radio Interference Elimination, Stanford Research Institute, Calif., Progress Rpt. No. 4, Sept. 15, 1951, (AD-222 175).

Donald L. Benedict, Radio Interference Elimination, Stanford Research Institute, Calif., Progress Rpt. No. 5, Dec. 15, 1951, (AD-222 176).

44. R. G. Klouda, Requirements of Measurements of Shielded Installations, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, pp. 460-472, (AD-276 205).

This paper covers both prefabricated shielded enclosures and shielded enclosures which are constructed as an integral part of a building. The problems associated with personnel doors, ventilating openings, entrance of power lines and plumbing, and illuminating the enclosure are also discussed. The selection of a shielding material is also treated.

45. Barton L. Conard, A Report on the Design and Construction of a Shielded Mobile Laboratory, Ace Engineering and Machine Co., Inc., Huntingdon Valley, Pa., Contract AF 30(602)2304, Proj. 5570, Aug. 2, 1961, (AD-326 550).

46. E. Squire, Research Leading to Improved Structural Design for Ground Electronic Applications, Polytechnic Institute of Brooklyn, Nov. 1953, (AD-25 088).

47. D. L. Hollway, Screened Rooms and Enclosures, INSTITUTE OF RADIO ENGINEERS (AUSTRALIA) PROCEEDINGS, Vol. 21, pp. 660-668, Oct. 1960.

48. J. Quine, Screened Room Calibration Factors at Low Frequencies, Rensselaer Polytechnic Institute, April 1954, (AD-49 255).

49. R. H. Titley, Shielded Room for High-Voltage Test, ELECTRICAL WORLD, Vol. 120, pg. 2078, Dec. 11, 1943.

This article describes briefly a shielded room that was used in determining RFI characteristics of bushings, pin and suspension insulators. No. 10 gauge copper sheet was used as shielding. The power supply was not filtered.

50. C. C. Borden, Shielded Rooms for Electronic Equipment, ARCHITECTURAL RECORD, Vol. 130, pp. 195-196, Sept. 1961.

51. A. R. Kall, F. Kugler, The Shielded Test Cells of the Titan ICBM Test Facility, The Martin Company's Denver Division, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, pp. 295-304, (AD-253 015).

This paper describes the architectural and construction details of six electromagnetically shielded test cells, each over 100 feet high. Methods of welding shielding material, installation of wave-guide air inlets, power and signal filters, and inspection test methods are described. Although not fully met, the original intent was to have a shielding effectiveness of 100 db in the frequency range of 60 cps to 10 kmc.

52. Cyril P. Durnovo, Shielding an Enclosure, ELECTRONIC INDUSTRIES, Vol. 21, pp. 112-114, Jan. 1962.

The author defines attenuation, gives a brief description of single shielded type, double shielded isolated wall type, and double shielded cell type screen rooms, and examines other factors such as frequency, type field, and construction features.

53. R. B. Schulz, D. P. Kanellakos, Shielding Enclosure Performance Utilizing New Techniques, INSTITUTE OF RADIO ENGINEERS INTERNATIONAL CONVENTION RECORD, Vol. 9, pp. 19-36, part 8, 1961.

54. C. Vasaka, Theory, Design, and Engineering Evaluation of R-F Shielded Rooms, Aeronautical Electronic and Electrical Laboratory, Naval Air Development Center, Johnsville, Pa., Aug. 1956, (AD-117 564).

This report includes the following: (1) basic theory of shielding in a form suitable for direct application to design and construction of shielded rooms, (2) graphs and tables of the shielding effectiveness of solid metal barriers for 60 cps to 10,000 mc, (3) compilation of pertinent factors affecting shielding measurements, (4) development of a shielding effectiveness test.

55. A. M. Intrator, The Use of Steel Sheet for the Construction of Shielded Rooms, COMMUNICATIONS AND ELECTRONICS, No. 72, pp. 599-605, Nov. 1953, (also condensed in ELECTRICAL ENGINEERING, Vol. 72, pg. 809, Sept. 1953).

Because of the high cost of copper and its scarcity during national emergencies, other materials were sought. A room was constructed of 24 gauge TRAN-COR-72 sheet steel. Wave-guides below cut-off were employed. Difficulty was experienced on door contacts. Theoretical shielding effectiveness was compared with experimental values which were derived by use of a magnetic dipole radiator. It was concluded that sheet steel could be used, with

attenuation of 46 db at 15 kc and more than 160 db at 1 to 10 mc obtainable.

SHIELDED CABLES

56. Arnold L. Albin, Applying Shielded Cables to Reduce Interference, Filtron Company, Inc.

    General rules for cable selection are given: (1) unshielded wire for external power circuits (115 v, 400 cps and 28 v d.c.), (2) shielded wire for multiple-ground a-f or power circuits, (3) twisted pair for a-f circuits with single ground and for internal power circuits, (4) shielded twisted pair for single-point ground circuits, and for multiple-ground circuits where maximum low-frequency isolation is required, (5) coaxial cable for transmission of r-f pulses, high frequencies, and where impedance matching is critical. The author stresses separation of power and signal cables, shielding of all r-f cables, and good grounding.

57. Applying Shielded Cable to Reduce RFI, ELECTRONIC DESIGN, pg. 48, Jan. 7, 1962.

58. Development and Evaluation of Shielded Lead-In Provisions, Naval Air Test Center, Patuxent River, Md. Rpt. No. 1, Final, Jan. 11, 1954, (AD-37 368).

59. William J. Mashek, Development of a Two-Conductor Shielded Cable Connector for Use in Missile Firing Circuits, Amphenol-Borg Electronics Corp., Chicago, Ill., Quarterly Tech. Prog. Rpt. No. 1, Sept. 28, 1961, (AD-265 827).

    "An investigation was begun on parts and assembly techniques leading to and including the development of a two-conductor shielded cable connector suitable for use in missile firing circuits. Studies are being conducted to determine the feasibility and means of meeting Navy objectives and also to prepare a suitable electrical testing procedure which will be used to evaluate the shielding effectiveness of the connector to be developed. The current areas of study and investigation dealt with the developmental objectives, the preliminary connector design concepts, and the evaluation of shielding effectiveness."

    William J. Mashek, Development of a Two-Conductor Shielded Cable Connector for Use in Missile Firing Circuits, Amphenol-Borg Electronics Corp., Chicago, Ill., Quarterly Tech. Prog. Rpt. No.2, Dec. 28, 1961, (AD-272 394).

William J. Mashek, Development of a Two-Conductor Shielded Cable Connector for Use in Missile Firing Circuits, Amphenol-Borg Electronics Corp., Chicago, Ill., Quarterly Techn. Prog. Rpt. No. 3, March 28, 1962, (AD-275 856).

60. S. L. Shive, Effectiveness of Conduit as r.f. Shielding, ELECTRONICS, Vol. 19, pg. 160, Feb. 1946.

This paper describes a laboratory method of evaluating the shielding effectiveness of conduit and discusses a number of typical measurements. Graphs are presented to show the shielding effectiveness of conduit of various thickness and of various metals. Measurements are also made on flexible conduit.

61. Louis V. King, Electromagnetic Shielding at Radio Frequencies, PHILOSOPHICAL MAGAZINE, Vol. 15, pg. 201, Feb. 1935.

62. Evaluation of 2 and 4 Conductor Cable, Lockheed Aircraft Corp., Sunnyvale, Calif., Rpt. No. TA 15,053, Nov. 20, 1961. (AD-275 202).

"Performance evaluation tests were conducted of 2 and 4 conductor shielded electrical cables in accordance with reliability test procedure no. 299."

63. Examination of Lines Variously Shielded to Avoid Radio Interference, U. S. Army Air Forces, AAF ATSC T-2, Translation 519, Feb. 1946, (PB-23 565).

64. J. D. Meindl, E. R. Schatz, The External Electromagnetic Fields of Shielded Transmission Lines, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, pp. 388-405, (AD-253 015).

"A theoretical analysis of the problem of leakage from shielded transmission lines is presented. The external or leakage fields of the coaxial and shielded pair transmission lines are related to the internal excitation of the lines and their physical properties. The analysis method used is a direct extension of a classical perturbation technique used to calculate the attenuation in high frequency transmission lines and waveguides. Since a well-designed shielded transmission line operated "nearly" TEM mode, the transverse field pattern in the line dielectric is substantially the static configuration and only a relatively small component of axial electric intensity exists....Results

achieved show that the electric and magnetic fields depend upon the shield properties as well as the line dielectric constant....."

65. Ernest F. Weinberger, Louis Auerbach, Investigation to Determine the Radiation from Simulated Shipboard Installations of Armored Power Cables, Material Lab., New York Naval Shipyard, Brooklyn, Final Tech. Rpt., Feb. 5, 1958, (AD-156 657).

"The shielding effectiveness was determined of the metallic armor of certain cables and grounding techniques which provide most effective shielding. Results showed that when a large portion (10 feet) of armor is stripped from an armored cable, the radiation emanating from the cable is approximately the same as that emanating from a cable whose armor is terminated to ground through a large loop or is not grounded at all. Previous work completed under this project indicated that the size of ground loops at the terminals of the armored power cable is a major factor in achieving the maximum shielding effectiveness of the armor. The work showed that coaxial type terminals at both ends of the cable provide the greatest shielding effectiveness, varying between 35 and 50 decibels, depending on frequency and other variables. Addition of a ground on the armor at the center of a coaxially grounded cable affords no over-all improvement in shielding effectiveness."

66. K. Ikrath, Leakage of Electromagnetic Energy from Coaxial Cable Structures, Army Signal Research and Development Laboratory, Fort Monmouth, N. J., Tech. Rpt. No. 1964, April 1, 1958, (AD-201 199).

"A better understanding of the behavior of electromagnetic leakage fields emanating from braid shielded coaxial cables is obtained. It is shown that a braid surface EMF per unit length which is linked to the magnetic leakage-flux distribution in the braid apertures tends to support a slowly propagating surface wave along the cable. At higher frequencies end effects play an important role in the shaping of the leakage radiation fields which acquire the typical tilted multilobe patterns of slow wave radiators. Measures regarding the suppression of leakage through cable braids employing concentration and hysteresis type dissipation of leakage energy in ferrite braid coatings is suggested. The initiation of an investigation of the practicality of utilizing the phenomena associated with leaky

braid shielded cables for the design of slow wave radiators and surface wave launchers is recommended."

67. P. J. Bearer, B. A. Firweather and others, Project Milcest, Bell Telephone Laboratories, Inc., Whippany, N. J., Quarterly Prog. Rpt. No. 11, Oct. 31, 1961, (AD-266 930).

"A brief field test was conducted concerning radio-frequency field intensities and resulting interference in coaxial cable CX-4245/G. Tests were made on several lengths of cable at 3 frequencies, with the cable on the ground or supported alone on a pole line. Measurements were made with the interfering radio transmitter several miles away and, at one frequency, in close proximity to the cable. Measurements were also made with a mobile transmitter at constant range but at several angular positions with respect to the cable run. An interference directivity pattern for the cable was developed. To compare interference measurements on the CX-4245 coaxial cable, which consists of a twisted pair of coaxials, and computations of interference based on a single coaxial, the effect of the presence of a second coaxial on interference pickup was calculated. Results of computations, based on the general theoretical equation, of the ratio of resulting interference to the intensity of the radio field are presented."

P. J. Bearer, C R. Crue and others, Project Milcest, Bell Telephone Laboratories, Inc., Whippany, N. J., Quarterly Prog. Rpt. No. 10, July 31, 1961, (AD-262 745).

68. C. W. Harrison, Jr., R-F Shielding of Cables, AMERICAN SOCIETY OF NAVAL ENGINEERS JOURNAL, Vol. 73, pp. 529-533, Aug. 1961.

The author shows how complete r-f shielding of a conductor is necessary in order to avoid undesired pickup. Several cable shielding arrangements are examined qualitatively for their effectiveness at selected frequencies.

69. L. Krugel, Screening by Outer Conductors in Flexible Coaxial Cables, Royal Aircraft Establishment (Great Britain) April 1958, (AD-218 468).

70. E. T. Pfund, Jr., J. E. Russell, Capt. Bard Suverkrop, The Shielding Effectiveness of Concentric High Frequency Transmission Lines, Proceedings of the 6th Conference on

Radio Interference Reduction, Armour Research Foundation, pp. 360-371, Oct. 1960, (AD-253 015).

"The relative shielding effectiveness of several concentric lines has been experimentally determined. Relative interference considerations for standard and corrugated tubing of copper, aluminum, nickel-plated copper, stainless-clad copper, and stainless-clad coin silver are presented for ceramic, plastic, and air-insulated transmission lines from 150 kc to 28 Mc."

71. F. H. Godding, H. B. Slade, Shielding of Communication Cables, ELECTRICAL ENGINEERING, Vol. 74, pg. 524, June 1955.

The authors point out that the theory of shielding is fairly well established when applied to continuous metal tubes, but the effectiveness of metal tapes and braid has to be determined empirically. The effects of frequency and of electric versus magnetic fields are discussed for various shields. A graph is presented to show the shielding effect of various materials, both as solid tubes and as braids and tapes.

72. Study of Tubular Shielding Conduit, Technicraft Laboratories, Inc., Thomaston, Conn., Final Report, 1949, (PB-99 517).

73. Wire Mesh Makes Flexible R-F Shields, ELECTRONICS, Vol. 33, pp. 90-92, Oct. 21, 1960.

This article describes the manufacturing processes in making r-f gasketing material and flexible shields from knitted wire mesh.

74. J. Sell, Wire Shielding Values, ELECTRONICS, Vol. 32, pg. 88, Nov. 13, 1959.

This article presents and describes a nomogram which can be used to determine the percent coverage, number of wires per carrier, and angle of braid with cable axis for flexible shielded cables. The amount of shielding afforded is not included as a parameter.

GROUNDING, BONDING, GASKETING

75. V. Pulsifer, Bonding Materials, Metallic Mating Surfaces: Low RF Impedance, Armour Research Foundation, Chicago, Ill., Jan. 1954, (PB-111 930).

76. Gary Steven, W. C. Troy, Bonding Materials, Metallic Mating Surfaces: Low RF Impedance, Armour Research Foundation, May 1952, (PB-107 359).

77. C. B. Pearlston, Case and Cable Shielding, Bonding, and Grounding Considerations in Electromagnetic Interference, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. RFI-4, No. 3, pp. 1-16, Oct. 1962.

This paper attempts to assemble concisely the theory and techniques relating to shielding, bonding, grounding, and cable selection, all basic techniques in electromagnetic interference reduction. Topics covered include shielding theory, selection of shielding materials, optimum enclosure design, interconnecting cabling, magnetic and electrostatic coupling, ground currents and shield grounding, and design guides.

78. O. P. Schreiber, S. Nellis, Design of Combination Fluid or Pressure and RF Gaskets, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 340-355, Feb. 1957, (AD-234 211).

"This paper discusses the design of combination pressure and RF gaskets. Techniques for the design of pressure gaskets alone are discussed first, including some simple rules for improving sealability. The design of RF gaskets is then reviewed. Combination gasket design is developed by combining the design procedures of both pressure gaskets and RF gaskets."

79. Design and Applying RFI Shields and Gaskets, ELECTRONIC DESIGN, pg. 62, Sept. 27, 1962.

80. W. E. Stinger, Evaluation of Seams and Gaskets Used in Shielding Enclosures and Development of Correctives for Improvement, Naval Air Development Center, Rpt. No. NADC-EL-52139, Feb. 3, 1953, (AD-9 494).

81. Irwin M. Newman, Arnold L. Albin, An Integrated Approach to Bonding, Grounding, and Cable Selection, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, pp. 434-459, (AD-276 205).

This article discusses the RFI problem at a government missile checkout complex. The interference was traced to poor grounding, automotive vehicles, fork-lift trucks, adjacent r-f equipment, and power

generating equipment. Solutions to the problems are presented along with pictures of shielding and grounding techniques applied. Graphs showing comparisons of various shielded cable grounding methods are included.

82. Locating Grounds in Shielded Room, ELECTRONICS, Vol. 20, pg. 134, Oct. 1947.

83. Verne Pulsifer, A. J. Hoehn, Low-Impedance Gaskets for Radio Frequency Applications, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, pp. 290-304, (AD-76 686).

"This paper describes the work performed to develop a gasket material which will prevent radio frequency energy from escaping at joints in closed containers while simultaneously effecting a gas-tight seal. A preformed gasket was designed which shows superior interference-reduction characteristics. A gasket cement consisting of metal particles in a suitable binder also was developed which approaches the properties of welded metal from the standpoint of r-f shielding. General principles of gasket design are discussed including type, orientation, and number of conductors in the gasket, and the effects of pressure and flange material. Testing procedures...are outlined in detail."

84. Radio Frequency Gasketing, ELECTRONIC DESIGN, pg. 46, Feb. 17, 1960.

85. O. P. Schreiber, RFI Gasketing--How to Use It, ELECTRONIC EQUIPMENT ENGINEERING, Vol. 9, pp. 91-93, March 1961.

86. G. Failla, "Shielded Contact" Grounding Key for Electromotors, Atomic Energy Commission, Nov. 10, 1947, (TIP G U3726).

87. Shielding and Grounding Techniques, Naval Civil Engineering Lab., Rpt. No. TN 435, 1962, (AD-279 882).

88. Structurals Play An Electronics Role in Transmitter Building, ENGINEERING NEWS RECORD, Vol. 162, pp. 34-35, April 2, 1959.

Some of the grounding practices in the construction of a 25 ft. high, 25,000 sq. ft. transmitter building at Cutler, Maine, are described.

89. Richard B. Schulz, Evaluating Shielded Enclosures, TELE-TECH AND ELECTRONIC INDUSTRIES, Vol. 13, pp. 75, 166-168, Feb. 1954.

The author discusses the different meanings and misuses of the terms "attenuation" and "insertion loss". The methods of measuring attenuation and insertion losses are discussed, and the advantages and disadvantages of the various methods are compared.

90. L. Castriota, The Evaluation of a Sectionalized Shielded Enclosure, Polytechnic Institute of Brooklyn, July 1952, (TIP G U24243).

This report discusses the various methods used to obtain shielding efficiencies of screened rooms, i. e., the "open-door, closed-door", "inside-outside", and "uniform field" methods. In view of the disadvantages of these methods, an alternate method is proposed and used in testing a cell-type shielded room. Methods of obtaining the attenuation characteristics of the power line filters are also discussed.

91. W. E. Stinger, Evaluation of Shielding Effectiveness Test Developed by Technicraft Laboratory, Aeronautical Electrical and Electronic Lab., Naval Air Development Center, Johnsville, Pa., Oct. 1953, (AD-30 862).

This report is the evaluation of a shielding effectiveness test of conduit as proposed by Technicraft Laboratories. The laboratory tests under this method compared favorably with theoretical values calculated on the basis of transfer impedance theory.

92. D. Arany, Experimental Model, Shielding Component Evaluator, Low Frequency, White Tuning Corporation, Final Rpt., July 1950, (TIP G R4391).

This article is a report on the development of an evaluator to measure the shielding effectiveness of flexible or rigid conduit from 0.25 to 1.5 inches i.d. and of various sizes of metal boxes between frequencies of 10 cps and 150 kc. Different configurations and spacings of several materials are investigated as factors in shielding.

93. W. C. Stoker, H. F. Hicks, An Investigation of Electromagnetic Coupling Devices for the Measurement of Noise

Fields, Rensselaer Polytechnic Institute, Feb. 1951, (ATI-108 035).

94. The Investigation of Measurement Techniques for the Shielding Effectiveness of Coaxial Cable, Signal Equipment Co., Inc., Seattle, Wash., Interim Development Rpt. No. 1, July 1 - Dec. 30, 1954, (AD-130 006).

"This report describes the research work on measurement techniques for the shielding effectiveness of flexible coaxial transmission lines. Included are the tests on various samples of flexible metal hose, used as additional shielding over standard RG-8/U; and the results obtained by the continuous recording of the longitudinal field distribution along samples of coaxial cable over the frequency range from 30 kc to 800 mc."

95. J. Johnson, W. Siddons, The Investigation of Measurement Techniques for Shielding Effectivness of Coaxial Cables, Signal Equipment Company, Inc., Aug. 1956, (AD-84 054).

96. Measuring Effectiveness of Shielding Materials, ELECTRICAL MANUFACTURING, Vol. 52, Aug. 1953.

97. H. E. Dinger, J. E. Raudenbush, Measuring the Shielding Efficiency of Screened Enclosures, Naval Research Lab., Rpt. No. 3908, Dec. 14, 1951, (ATI-122 259) (TIP G U20197).

The authors describe the "uniform-field" method of measuring attenuation which was used for evaluating a double-shielded and a cell-type room. The effect of weathering was noted on the shielding efficiency of the cell-type room. A transfer-impedance method of evaluating shielded enclosures is also described.

98. T. M. Good, A Method of Evaluating the Effectiveness of Radio Frequency Gasket Materials, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1959, pp. 601-621, (AD-235 099).

This paper is concerned with describing a method of evaluating the effectiveness of radio-frequency gasket materials. Frequency ranges of 0.15 to 1000 mc are considered. Test setups, results, and problems encountered are discussed.

99. D. E. Foster, C. W. Finnigan, Methods of Measuring the Effectiveness of Electrostatic Loop Shielding, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 31, pp. 253-255, June 1943.

"In the design of radio receivers employing electrostatically shielded loops, difficulty in measuring the effectiveness of the loop shielding in the laboratory is usually encountered. This paper describes a method using a short rod antenna connected to a conventional standard-signal generator which has been found to be convenient to operate and capable of producing consistent results. The effectiveness of shielding is determined as the ratio of the effective height of the loop as a magnetic field collector to its effective height as an electric-field collector."

100. D. P. Kanellakos, R. B. Schulz, L. C. Peach, A. P. Massey, New Techniques for Evaluating the Performance of Shielded Enclosures, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 526-559, Oct. 1959, (AD-235 099).

The shielding effectiveness of an enclosure was measured at a low (15 kc) frequency utilizing a transmitting loop which surrounded the enclosure. A small 12" loop was used for the receiver in the center of the room. At mid frequencies the effects of standing waves within the enclosure on the radiation resistance of the receiving dipole were considered. The transmitting antenna outside the room was also a dipole. For high frequencies (9.375 kmc) a radar transmitter was used as a source. Diagrams are given of test set-ups and results are plotted.

101. J. A. Allen, A Proposed Standard for Testing the Shielding Effectiveness of Coaxial Cables and Shielding Material, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 372-387, Oct. 1960, (AD-253 015).

The proposed technique evaluates the leakage electromagnetic energy by measuring the lumped constant voltage that is produced at the end of a cylindrical test enclosure. The coupling of electromagnetic fields between the inner and outer surfaces of a cylindrical shielding sample is considered. Test equipment and measuring techniques are given.

102. Edward R. Schatz, Maurice E. Taylor, Research Leading to the Development of a Shielding Effectiveness Tester, Carnegie Institute of Technology, Pittsburgh, Pa., Quarterly Prog. Rpt. No. 3, Dec. 15 - March 15, 1957, (AD-140 899); Quarterly Prog. Rpt. No. 4, March 15 - June 15, 1957, (AD-155 260); Quarterly Prog. Rpt. No. 5,

June 15 - Sept. 15, 1957, (AD-155 259); Quarterly Prog. Rpt. No. 6, Sept. 15 - Dec. 15, 1957, (AD-157 558); Final Rpt. June 15, 1956 - June 15, 1958, (AD-213 322).

103. D. P. Kanellakos, H. M. Sachs, Revision of Standards for Measurements of Shielding Effectiveness of Enclosures, Armour Research Foundation, ARF Proj. E108, Oct. 1959, (PB-157 574).

104. H. E. Dinger, J. E. Raudenbush, A Technique for Measuring the Effectiveness of Various Shielding Materials, Naval Research Lab., Rpt. No. 4103, Jan 22, 1953.

The authors describe a method whereby the shielding effectiveness of small samples of various materials, including wire mesh and conductive coatings, can be tested in high- and low-impedance fields. Samples are inserted between two shield cans containing small transmitting and receiving elements. Calculated and measured values are compared for several samples.

GENERAL ARTICLES ON SHIELDING

105. E. Ornstein, Attenuation of E-M Radiation by Sea Water, Naval Research Lab., Rpt. No. 5280, April 1, 1959.

This report presents a plot of attenuation (db/yd) of sea water versus frequency--10^3 to 10^{21} cps. Attenuation increases with frequencies up to 3 X 10^6 db/yd at approximately 10^{12} cps.

106. J. D. Noyes, Commercial Mobile Radio Interference Shielding, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 258-264, Oct. 1960, (AD-253 015).

The present-day automobile is treated as a source of radiated electromagnetic interference. The various sources in the automobile and the interference characteristics of each source are considered. The effects of these RFI signals on a radio receiver are presented. A commercially available suppression kit is described in great detail.

107. L. W. Thomas, Control of Interference Through Basic Design, U. S. BUREAU OF SHIPS JOURNAL, Vol. 6, pg. 31-33, Sept. 1957.

"This paper deals not with the suppression of radio interference, but with the control of it in the basic design of equipments. Both electronic and

electromechanical devices are considered and design practices pointed out for each case."

108. A. R. Anderson, Cylindrical Shielding and Its Measurement at Radio Frequencies, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 34, pp. 312-322, May 1946.

"The effectiveness of shields from the point of view of the wave theory of shielding is discussed. Specific consideration is given to cylindrical shielding against low-impedance fields and its measurement at radio frequencies. Various methods of measurement are discussed briefly.... Experimental results obtained.....from 200 kc to 10 Mc are given. Tests at various frequencies on thin-wall copper tubes of different thicknesses are shown to be in agreement with the results predicted by theory. Included are data on metal tubes, wire braids, coaxial cable, and flexible-shielding conduits..... Various factors affecting test results are considered and formulas are given for correcting results obtained on exceptional specimens having abnormally high resistance."

109. A. L. Albin, H. M. Sachs, Design of Electronic Equipment for Radio-Interference Reduction, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS I (COMMUNICATIONS AND ELECTRONICS), Vol. 75, pp. 352-357, July 1956.

"The control of radio interference is a serious problem to both designers of electronic equipment and to military operational activities. Some of the critical areas of design that have affected equipment and system performance in the field are discussed herein. Several types of equipment for ground and air-borne applications are discussed, including radar, communications, and navigation apparatus. The effectiveness of practical suppression techniques such as shielding and filtering is also considered. Requirements of the current interference specifications are reviewed and techniques discussed for making conducted and radiated measurements of continuous-wave and broadband interference sources."

110. C. F. Davidson, J. C. Simmonds, Effect of Spherical Screen Upon An Inductor, WIRELESS ENGINEER, Vol. 22, pp. 2-5, Jan. 1945.

The change in impedance of an inductor due to the presence of a circular screen is calculated and curves are present which enable the increase in

resistance and decrease in inductance to be computed.

111. H. Kaden, Electromagnetic Screens with Joints and Gaps, WIRELESS ENGINEER, Vol. 21, pg. 84, Feb. 1944.

The object of this paper is to investigate the effects of joints and gaps in electromagnetic screens. Two treatments are present: joints parallel and at right angles to eddy currents.

112. S. Levy, Electromagnetic Shielding Effect of An Infinite Plane Conducting Sheet Placed Between Circular Coaxial Coils, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 24, pp. 923-941, June 1936.

"In apparatus employing amplification it is frequently necessary to isolate certain circuit elements from electromagnetic disturbances. In circuits employing high amplification the amount of shielding required for isolation may be extremely high, and the usefulness of the device may be impaired due to inadequate shielding. The theory of shielding against magnetic and electrostatic fields are discussed and examined. A bibliography of articles which treat the subject of shielding is given."

113. Electromagnetic Shielding Principles, Vol. II of Investigation of Interference from Radar Modulators, Rensselaer Polytechnic Institute, March 1, 1956, (AD-91 298).

This volume of the report covers electromagnetic leakage from coaxial cables, estimation of required shielding (for cabinets and pulse cables), and conducted interference.

114. W. Lyons, Experiments on Electromagnetic Shielding At Frequencies Between One and Thirty Kilocycles, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 21, pg. 574, April 1933.

"This paper describes a method used in measuring the ratio of magnetic field intensities within conducting cylindrical and spherical shells to that outside, values being given for various frequencies between 1000 and 30,000 cycles per second of the exciting field and various lengths and radii. A theoretical derivation of a shielding formula is given for a thin spherical shell and a cylindrical one of infinite length. Satisfactory agreement between theory and observation is found in the case of the sphere and in cylinders of lengths greater than their diameters."

115. Hsu Chang, Fields Associated With Ellipsoids With Applications to Shielding, Thin Films, and Twistors, Carnegie Institute of Technology, Pittsburgh, Pa., Feb. 1959, (AD-214 973).

"Static fields associated with a ferromagnetic ellipsoid with uniform magnetization or paramagnetic hollow spheriod immersed in an originally uniform or non-uniform field are considered. The hollow spheroid (prolate or oblate) approximates a wide variety of geometries, ranging from an infinite hollow cylinder to a rod of finite length, from two parallel plates to a disc. Thus the solutions permit calculation of: (a) Shielding factors of hollow spheroids; (b) Fields outside a circular or elliptic thin film; and (c) Demagnetizing field in a hollow twistor, and the field outside the twistor. The solutions may be applied to both linear and "square-loop" magnetic materials."

116. D. T. Geiser, Filtering and Shielding the Station Receiver, QST, Vol. 42, pp. 27-29, Aug. 1958.

This article describes "jury-rig" modifications to a ham receiver that resulted in reduced stray pick-up and radiation.

117. C. M. Jorgensen, "Foiling" Magnetic Interference, RESEARCH AND DEVELOPMENT, Vol. 12, pp. 106-107, Oct. 1961.

Several new types of foil shaped alloys that are useful in magnetic shielding are described. Methods of reducing the reduction in permeability as flux density increases are suggested.

118. Robert W. Heath, How to Control Extraneous Magnetic Fields, INDUSTRIAL LABORATORIES, Vol. 10, pp. 8-11, April 1959.

The author lists some common laboratory equipment that is affected by magnetic radiation. Other than pointing out that magnetic shielding can be best accomplished by use of magnetic-type alloys, the main topic is the construction of a probe for picking up magnetic radiation.

119. O. P. Schreiber, Is Your Rig R-F Tight, QST, Vol. 37, pp. 29-30, Aug. 1953.

This article describes the use of r-f gasketing material (called electronic weatherstripping by the author) in suppressing TVI from ham transmitters.

120. Spring, Magnetic Shielding, ELECTRICAL MANUFACTURING, Vol. 61, pp. 138-139, Feb. 1958.

121. Magnetic Shielding, TELE-TECH AND ELECTRONIC INDUSTRIES, Vol. 14, pg. 153, May 1955.

122. Schweizor, Magnetic Shielding Factors of A System of Concentric Spherical Shells, JOURNAL OF APPLIED PHYSICS, Vol. 33, pp. 1001-1003, March 1962.

123. D. E. Longmire, Magnetic Shielding Practice in Electronic Packaging, ELECTRO-TECHNOLOGY, Vol. 71, pp. 63-66, Jan. 1963.

124. R. C. Looser, J. C. Simmonds, C. F. Davidson, Power Loss in Electromagnetic Screens, WIRELESS ENGINEER, Vol. 23, pp. 8-15, Jan. 1946.

"A method is developed which enables the increase in resistance of an inductor to be calculated when a screen consisting of circular loops of wire is brought near it. The calculated resistance increase agrees within about 20% or better with experimental values obtained by measurement on small screens."

125. C. S. Vasaka, Problems in Shielding Electrical and Electronic Equipment, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-N5507, June 1955, (AD-68 874).

This report discusses the over-all problem of shielding against RFI in the frequency range 14 kc to 10 kmc. Shielding effectiveness of 50 to 100 db are desirable. The negligible shielding effect of a ship or aircraft structure is discussed. Tables of reflection and absorption losses are given for iron and copper at various frequencies. Shield discontinuities are also discussed.

126. J. W. Shrecengost, Radio Interference: Control Plan and Test Plan Autopilot Gyroscope Control Group #27-41002, Convair-Astronautics, San Diego, Calif., Rpt. No. AZN-27-111, April 16, 1959, (AD-242 633).

127. J. F. Fischer, Jr., Radio Interference. Control Plan and Test Plan Autopilot Programmer Canister #27-41001, Convair-Astronautics, San Diego, Calif., Rpt. No. AZN-27-098, March 6, 1959, (AD-242 632).

128. J. F. Fisher, Jr., Radio Interference. Control Plan and Test Plan Autopilot Servo-Amplifier Canister #27-41000,

Convair-Astronautics, San Diego, Calif., Rpt. No. AZN-27-109, April 9, 1959, (AD-248 702).

129. W. R. Johnson, Radio Interference. Control Plan and Test Plan Propellant Utilization Canisters #27-43000 - #27-43001, Convair-Astronautics, San Diego, Calif., Rpt. No. AZN-27-090, Feb. 4, 1959, (AD-242 631).

130. J. F. Fischer, L. E. Robbins, Radio Interference Control Plan and Test Plan Strobe Light System #27-11236, Convair-Astronautics, San Diego, Calif., Rpt. No. AZN-27-125, July 7, 1959, (AD-248 241).

"The equipment canister is a completely enclosed metal unit, broken only by the lens. Three major circuits are contained which may generate electrical interference: (a) high voltage capacitor, flash-tube, and interconnecting wire (high voltage discharge circuit), (b) charging circuit which includes power transistors, power transformer and associated rectifiers and filter, and (c) control circuitry which includes provision for initiating the charging operation, generating the flashing rate signal and triggering the flash-tube. Low signal level circuitry will not be employed and each individual circuit will be designed for minimum susceptibility to conducted and radiated interference."

131. G. Weinstein, H. H. Howell, G. P. Lowe, B. J. Winter, Radio-Noise Elimination in Military Aircraft, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 63, pp. 793-795, Nov. 1944.

"Discusses the effects of electrical transients, which result from the operation of electrical equipment, on the reception of desired signals in airborne receivers, and describes the methods by which the noise is coupled into the receiver. The design necessary to eliminate radio-noise is discussed with the main emphasis on filters in the power input to the receiver. Curves of power-line noise in μv vs receiver audio output for several typical installations; and a laboratory setup for determining threshold of conducted radio noise for a receiver are shown."

132. Edward S. Ida, Reducing Electrical Interference, E. I. duPont de Nemours and Company, CONTROL ENGINEERING, pp. 107-111, Feb. 1962.

The author discusses several types of interference and ways of eliminating it. He discusses points to

be grounded, twisting of lines, shielding of cables, and line balancing.

133. RFI Control--Clearing the Air, ELECTRONIC DESIGN, pg. 37, Sept. 27, 1962.

134. Scattering of Electromagnetic Waves by Ultrasonic Beams, Emerton, Inc., Silver Springs, Md., Quarterly Prog. Rpt. No. 2, March 30, 1962, (AD-274 809).

135. B. Roston, Screening at VHF, WIRELESS ENGINEER, Vol. 25, pp. 221-230, July 1948.

"The paper aims at examining the vhf screening properties of the various metallic surfaces which are economic and which may be readily adapted to production. An analysis of the problem of shielding shows that in the case of a receiver, where only the radiation field requires to be screened, a conducting sheet makes an efficient shield. The shielding of a source of a receiver near a source is relatively more difficult, since the induction field may predominate and only a thin surface layer of a shield is effective in neutralizing this component of the field. An experimental method has been developed by which the efficacy of various forms of metallic shield may be assessed. Tests upon electro-deposited steel specimens and sprayed-metal specimens have given results which confirm the theoretical deductions and determine the order of their screening efficacy."

136. T. S. E. Thomas, Screening Effect of Circular Disk, AMERICAN JOURNAL OF PHYSICS, Vol. 29, pp. 37-39, Jan. 1961.

"A theory of the effect of a circular metal disk in screening the electric field of a pole and the magnetic field of a radio-frequency dipole (eddy current screening) on the axis is developed in terms of spheroidal functions. The screening effectiveness is defined as the ratio of the screened to the unscreened field and curves are given showing its variation along the disk axis. In the electrical case the field is zero at a certain distance along the axis." This report, while not applicable to complete enclosure screening, can be used as a basis for application where complete screening is not necessary, i.e., where one component must be screened from another.

137. Moullin, Screening Properties of a Squirrel Cage of Wires, INSTITUTE OF ELECTRICAL ENGINEERS JOURNAL, Pt. 3,

Vol. 91, pp. 14-22, March 1944.

The energy which is radiated by a long current filament is screened by a squirrel cage of equally spaced thin wires. The factors of squirrel cage wire radius and separation and frequency are considered. No comparison is made with experimental values.

138. P. S. Rand, Shielding Against TVI, RADIO AND TV NEWS, Vol. 42, pp. 57-60, Sept. 1949.

This article describes how some of the basic shielding principles were applied to ham gear to reduce TVI.

139. John H. Morecroft, Alva Turner, Shielding of Electric and Magnetic Fields, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 13, pg. 477, Aug. 1925.

This article reports on the experimental investigation of the shielding of electric and magnetic fields for both constant and changing fields. The factors of frequency, shielding material, and shield discontinuities are considered.

140. Albert F. Murray, Shielding H.F. Interference, ELECTRONIC INDUSTRIES, Vol. 4, pp. 108-110, 142, Aug. 1945.

This article is basically a discussion of shielded rooms of the single shield, double shield, and cell type construction and line filters. Graphs are given of attenuation expected from various type screening materials.

141. Shielding High-Frequency Circuits Can Be Effectively Engineered, ELECTRICAL MANUFACTURING, Vol. 38, pp. 134-137, Sept. 1946.

142. W. Philbrook, Shielding In Hi-Fi Equipment, RADIO AND TV NEWS, Vol. 54, pp. 48-49, Dec. 1955.

The author discusses the desirable features of magnetic and electric shields and gives several applications where shielding can be applied.

143. Shielding Principle Provides Electronic Micrometer, MECHANICAL ENGINEERING, Vol. 69, pp. 406-407, May 1947.

144. Shielding Principle Provides Electronic Micrometer, PETROLEUM ENGINEERING, Vol. 18, pg. 113, April 1947.

145. C. S. Vasaka. Short Cut to R-F Shield Design, ELECTRONIC INDUSTRIES AND TELE-TECH, Vol. 16, pp. 72-74, March 1957.

"Rule-of-thumb design commonly ignores reflection losses, resulting in over-designed equipment enclosures. The method presented here takes into account electric, magnetic, and plane wave reflection losses, and corrects for electrically thin sheets and shield discontinuities. Data for common shield designs have been calculated and are presented in extensive reference tables." Calculations are based on equations derived by Schelkunoff. Recommended treatment for various discontinuities in equipment cabinets are given.

146. Survey of All Available Information on Commercially Obtainable Conductive and/or Radio Frequency Absorbing or Attenuating Materials, Interference Consultants, Inc., 150 Causeway Street, Boston 14, Mass., Naval Civil Engineering Laboratory, Contract I. C., Jan. 1962.

Contains bibliography of 133 published articles on shielding plus bibliography of industrial reports in company files.

147. T. B. Owen, Very-High-Frequency Radio-Noise Elimination, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 63, pp. 949-954, Dec. 1944.

It is the purpose of this paper to outline generally the principles of radio noise elimination at all frequencies, and to show that the principles used for medium and high frequencies also apply at very high frequencies. Subjects treated include methods of radio-noise generation and transmission, common impedance coupling, elimination of RFI, and specifically RFI from aircraft-engine ignition systems.

CHAPTER XI

SUPPRESSION

The most time-saving and money-saving way of eliminating RFI is through the proper design of potential interference generators. However, since there are such a large number of potential generators, including everything from household appliances to radar equipment, such a proposal calls for the mass education of designers of many products. Proposals have been made by various groups that legal action be taken to curb the generation of RFI. In ref. (2), P. R. Coursey reports on a meeting which was held in England in 1944 at which time such proposals were made. Some of the types of legislation that could be used and some of the problems in enforcing such legislation were discussed. R. Davidson, in ref. (21), outlines some of the legal regulations which have been effected in England for the suppression of radio interference. These include compulsory fitting of suppressors on ignition systems of motor vehicles, suppression of interference to within certain limits on any small electric motor, and control of interference generated by refrigerators. In the United States the Federal Communications Commission is the regulatory body which is associated most directly with interference control. An example of the type regulations established by the F.C.C. is given in Chapter II, Radio Frequency Interference. The standards and specifica-

tions of the Department of Defense agencies, although not of a legal nature, have played an important role in ensuring RFI suppression techniques are applied to a vast array of products. Appendix A is a list of military standards and specifications which apply to RFI reduction and measurement.

Since the application of suppression devices must not alter the primary function of a device to any great extent, various suppression techniques are required. The most generally recognized techniques applied today are the use of choke coils, feed-through and by-pass capacitors, filters, non-linear devices such as diodes and transistors, resistive devices, and shielding principles.

One use of choke coils for RFI reduction is in transmission lines. C. V. Aggers points out in ref. (31) that they are not normally used to reduce radio noise at its source, but rather are used to attenuate the transmission of noise from certain sections of a circuit. He also points out that radio frequency noise may be reflected on the lines by a choke coil and that, unless the noise is eliminated by shunting to ground, the reflected noise voltages may actually increase the noise level.

The principle by which a coil acts as a suppression device is that it presents a high impedance to radio frequencies. This is apparent from the equation for reactance of a coil,

$$X = 2\pi f L$$

where f = frequency
L = inductance of coil

One of the limitations of coils is that they have small impedance to the low frequency components of radio noise.

Closely related to the choke coil is the by-pass capacitor. These two components make up the simplest type filters. The application of by-pass capacitors is based on the principle that they offer a low impedance to radio frequencies. However, because of the inherent inductance in the leads of a by-pass capacitor, there is a maximum limit to the frequency at which the by-pass capacitor offers a small impedance to RFI. During World War II the development of the stud type capacitor, so named because of a short, thick lead, raised this maximum frequency at which by-pass capacitors could be used from two to five megacycles. This was reported by S. L. Shive in ref. (122).

Shive continues with a discussion of the feed-through capacitor, which is illustrated schematically in Fig. XI - 1.

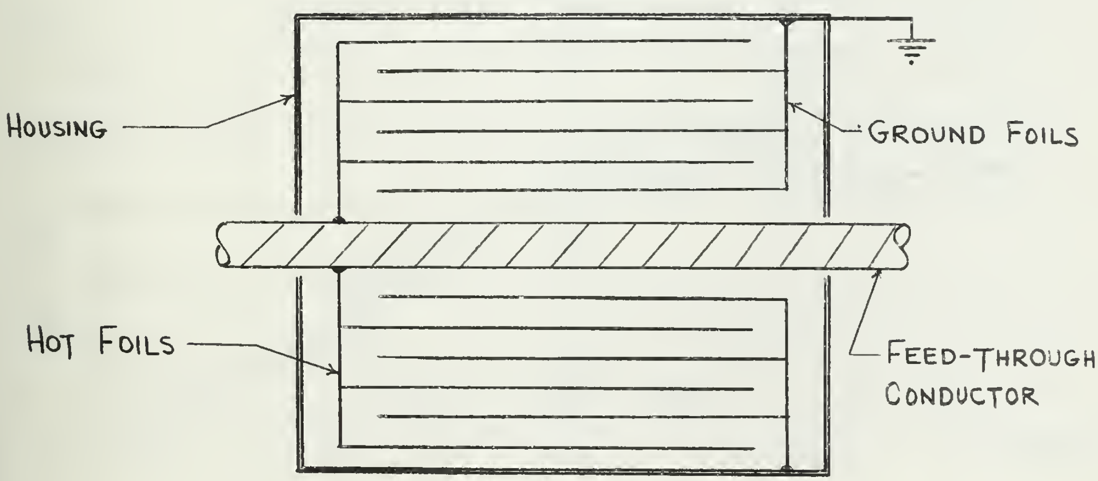

Fig. XI - 1 Schematic Diagram of a Feed-Through Capacitor

As can be seen, lead lengths are ultimately reduced to nothing. The development of the feed-through capacitor made capacitors applicable as a suppression device up to frequencies of 1000 mc.

The effectiveness of a suppression capacitor is measured by its "insertion loss". Insertion loss is defined as the ratio of voltages existing across a load impedance before and after "inserting" or connecting the suppressor to be tested in the circuit. In other words, the insertion loss tells how much the voltage of a specific frequency component at a load is reduced by the application of a capacitor. Insertion loss is normally expressed in decibels. Fig. XI - 2, extracted from ref. (122), compares the insertion loss of a typical feed-through capacitor and a similar valued lead type capacitor.

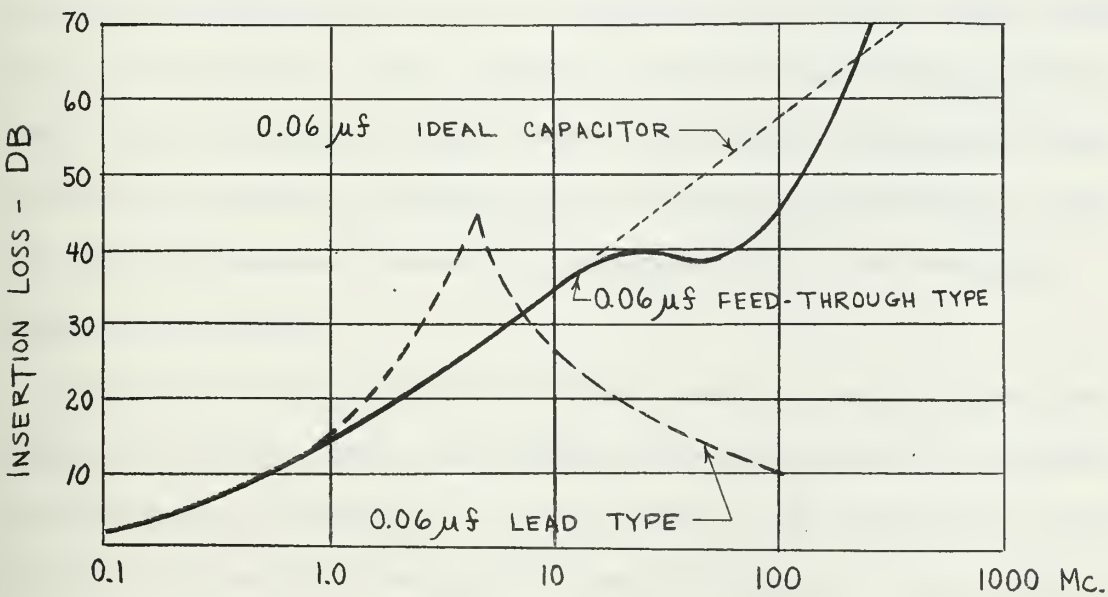

Fig. XI - 2 Insertion Loss Characteristics for a Typical Feed-Through Capacitor Compared to that of a Lead Type Capacitor

The small size and weight, excellent insertion loss characteristics, and relatively low cost has enhanced the use of feed-through capacitors as suppression devices. However, their effectiveness is also limited at lower frequencies.

Filters also play a large role in the reduction of conducted RFI. The principle of filters is to provide a low impedance path for desired signals and, at the same time, a high impedance path for undesired signals. Various types of filters have been investigated for use in RFI suppression, however the basic circuit configuration is usually of the pi or T type with inductors connected in series with the line to be suppressed and capacitors connected between the line and ground.

In ref. (15), Mervin H. First points out some of the design information which must be taken into account when selecting a RFI filter. Some items are current and voltage rating, power line frequency, duty cycle, operating temperature and altitude, required attenuation at various frequencies, maximum case dimensions, mounting arrangements, and terminal types to be used.

The use of non-linear devices, such as transistors and diodes, has also been considered for suppressors in switching and relay circuits. In ref. (25), G. E. Stannard, et al, give the principles behind the use of diodes. It is best explained by use of Figs. XI - 3 and XI - 4.

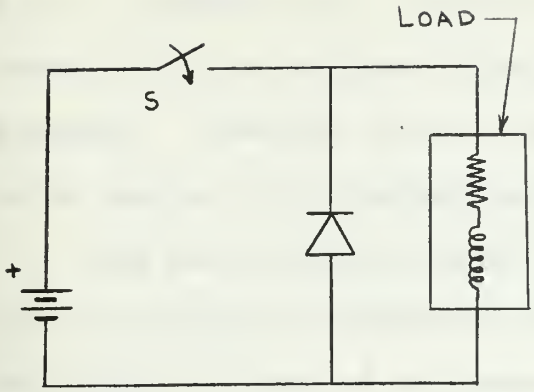

Fig. XI - 3 Shunt Diode Across Load

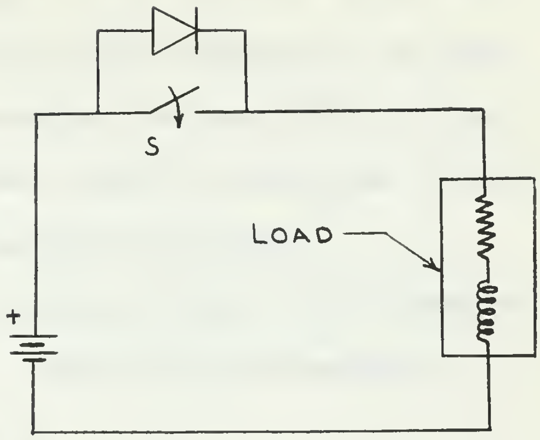

Fig. XI - 4 Shunt Diode Across Switch

In Fig. XI - 3, negligible current flows through the diode under steady state conditions, but when the switch is opened, the diode provides a low resistance path over which inductive current from the load may flow. The peak voltage appearing across the switch (where RFI is generated) is thereby limited to the sum of the battery voltage and the forward drop of the diode which may be quite small. Thus, high-voltage sawtooth discharges are eliminated, but this circuit is ineffective in retarding the gap voltage buildup. In Fig. XI - 4, the diode voltage-current characteristics must have a sharp knee at a voltage which is equal to, or somewhat greater than, the supply voltage. Thus, the steady-state current through the load will be essentially zero when the switch is open. When the switch is opened, the voltage across the gap immediately assumes the knee value. This circuit is capable of complete suppression of high-voltage

discharges but again cannot retard the buildup of gap voltages. Stannard also reported that noise reduction in the order of 30 db had been obtained with the use of diode suppressors. However, their use was largely restricted to circuits having large inductively-stored energies.

The use of distributed resistance leads in RFI suppression is covered in Chapter III, Ignition Interference. Shielding is covered in Chapter X.

Numerous reports have been prepared on the types of suppression techniques applied to specific equipments and are included in the bibliography for this chapter. The principles applied to each piece of equipment may be helpful in application of RFI controls to similar equipment.

CHAPTER XI
BIBLIOGRAPHY AND ABSTRACTS

1. Antenna Filters for Shore Station Interference Suppression, Balco Research Laboratories, Newark 2, N. J., Dec. 31, 1952, (AD-10 893).

This interim report describes the Zobel method of design for a fixed-cutoff filter and reports that standard m-derived design could not meet the contract requirements. Tests on variable-inductance-fixed capacitance designs for variable-cutoff filters are reported. Trap filter designs are also discussed.

2. P. R. Coursey, Aspects of Interference Suppression Under Post-War Conditions, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 92, pp. 21-22, Part III (Radio and Communication Engineering), March 1945; WIRELESS WORLD, Vol. 51, pp. 7-8, Jan. 1945.

This narrative is a brief of a discussion held at a British conference in November 1944. Topics discussed include the broader spectrum in which RFI control will be important after World War II, types of apparatus likely to be potential interference sources, and wider use of common electric equipment. The possibility of legal controls on RFI are also discussed.

3. John L. Pancoast, Contract Acceptance Tests of Sprague Type 97JX106A Interference Filter, Naval Engineering Experiment Station, Annapolis, Md., EED Rpt. No. 810152, Feb. 25, 1959, (AD-215 986L).

"The Sprague interference filter is intended as an interference reduction component in the model RC scaling and chipping tool. Tests indicated that the filter meets BuShips specifications except that the markings do not include the class designation."

4. John L. Pancoast, Contract Suitability Tests of Astron Type AF-1375-B Interference Filters Submitted by Polarad Electronics Corporation, Long Island City, New York, Naval Engineering Experiment Station, Annapolis, Md., EES Rept. No. 810110, Nov. 7, 1958, (AD-212 981L).

5. L. I. Knudson, The Design of Reactors for Radio Interference Filters, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 69, pp. 1294-1298, Pt. II, 1950.

Particular attention is focused on the design of

toroids. Curves are presented showing the relation between (1) number of turns, permeance, and inductance, (2) B vs. H, and (3) incremental permeability vs H for five magnetic materials.

6. L. Kahn, A. G. Kalstein, Development of Miniature Suppression Capacitors, Aerovox Corp., June 1952 (TIP G U23378).

The development of miniature suppression capacitors rated at 250 volts a.c.-d.c. 400 cycles, for operating temperatures of 125° C is described. Major problems encountered were sealing the capacitor can, making proper terminations, and smallness of size. Tables are given of the characteristics of the final product.

7. H. Goldberg, Dynamotor Filtering, RADIO NEWS, Vol. 29, pg. 13, March 1943.

8. M. B. Ewalt, Electrical Noise Suppression, MACHINE DESIGN, Vol. 26, pp. 161-166, Sept. 1954.

Common sources of RFI are listed and the four following methods of suppression are advocated: (1) noninductive capacitors, (2) feed-through suppression capacitors, (3) filters, and (4) application of electronic principles (bonding, shielding, etc.). Basic design criteria is given for selecting a method of suppression.

9. Electronic Interference Suppression, U. S. Navy Bureau of Yards and Docks Instruction 10380.1, Dec. 7, 1962.

This instruction deals with the basic aspects of electromagnetic interference produced by electrical, electronic, and mechanical equipment. The methods of eliminating interference to the greatest possible extent are outlined. The general limits of tolerable interference in the range of 14 kc to 1000 mc are also given in chart form. Acceptable measurement equipment and methods are included.

10. Harold G. Price, Eliminating Car Noise in 28-Mc Mobile Reception, QST, pg. 37, May 1947.

The author proposes methods of eliminating RFI which emanates from the car ignition, generator, front- and rear-wheel static, tire static, and voltage-regulator. The principle method is to eliminate RFI at its source.

11. T. F. Knapp, Engineering Study of Radio Interference Suppression, Lear, Inc., WADC technical rpt. 54-399, Nov. 1954, (AD-63 283).

A study of conducted radio interference is presented showing the effects of design factors such as commutator configuration and material; brush material, pressure and current density; air gap; and armature winding. The effectiveness of coils, capacitors, and internal and external filters as suppressors of generated interference is investigated. Interference measurement techniques and results are also presented.

12. J. C. Senn, Ferrites in Radio Interference Filters, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, Oct., 1958, pp. 458-474, (AD-234 212).

"This paper describes some of the special properties of ferrite magnetic core materials which can be used to advantage in the design of radio interference filters. It is shown that conventional design formulae can be adapted to account for these special effects in filters. Performance of typical filters using ferrites is demonstrated."

13. G. J. Wheeler, Filters for Electronic Equipment, ELECTRONICS, Vol. 18, pg. 200, July 1945.

The design of pi-type filters is discussed in this brief article. The author points out the dangers of (1) using too large an r-f choke, (2) resonance within the rejection band of the filter, (3) poor grounding, and (4) improper shielding of the output from the input.

14. W. A. Stirrat, A General Technique for Interference Filtering, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. RFI-1, No. 2, pp. 12-17, May 1960.

"With one exception, the radiation and leakage from a signal generator can be held below specified limits. Exception exists in the loop consisting of the signal generator power cord, the power main, the ground connection of the signal generator, and the signal generator itself. Signals passing through the line filter are resonated in this loop and these signals can only be reduced by mismatch or by reduction of the maximum power available. Since the nature of the loop is unpredictable, a

mismatch that will hold in every case cannot be provided. A limit on the maximum power available holds in every case. This maximum power theoretically can be measured and the limit which it should not exceed can readily be found. The load drawing maximum power from a three terminal network is found and the theory of measuring this maximum available power is developed herein. Also indicated are how a limit can be set on maximum available power and how a simple LC filter fails to provide reliable mismatch."

15. Mervin H. First, A Guide to RFI Filters, ELECTRONIC INDUSTRIES, Vol. 19, pp. 124-127, June 1960.

The author discusses the importance of the location of suppression devices and of complete specification of filter requirements. Ventilator openings are mentioned briefly. Two tables are included which list stock type suppressors which are commercially available.

16. J. D. Cooney, How to Suppress Radio Interference, ELECTRICAL MANUFACTURING, Vol. 54, pp. 109-128, Sept. 1954.

"A new problem is being placed on the desks of increasing numbers of design engineers. This is the problem of radio interference caused by electromechanical products and equipment. Military and Federal agencies already have begun concentrated drives to enforce existing laws and specifications. Indications are that the present tightened situation is only a forerunner of conditions to come and that suppression will one day be a primary part of every design project. The following article answers some fundamental questions on radio interference."

17. Joseph A. Allen, Insertion Loss Measurement Under Load, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1618, Jan. 3, 1955, (also found in Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 77-88, Feb. 1957, (AD-234 211)).

"This report describes procedures and equipment for measuring the insertion loss of radio frequency suppression filters with rated current applied. The basic functions of the test circuit and an evaluation of the equipment utilized are herein described. A brief definition of "insertion loss" and an explanation of the procedure for testing

the insertion loss of filters are included for information purposes. The "insertion loss" testing jig assembly described herein for mounting of and connecting to suppression components permits an accurate evaluation of the insertion loss of r-f suppression filters and feed-through capacitors of a large variety of sizes and shapes having terminals that may be oriented axially, skew, or at right angles with respect to each other."

18. Installation and Maintenance Handbook for Interference Shielding of Internal Combustion Engines, Department of the Navy, Bureau of Yards and Docks, NAVDOCKS P-278, Jan. 1963.

    This publication provides the information required to install, test, and maintain suppression shielding on engines.

19. Interference Filters, CONSUMER REPORT, Vol. 22, pp. 375-376, Aug. 1957.

20. F. H. Tooker, Interference-free A-M Reception, RADIO AND TV NEWS, Vol. 58, pg. 54, Nov. 1957.

    The author describes a power line filter that can be used to eliminate conducted interference in an a.c.-d.c. broadcast receiver. Types of interference which cannot be eliminated with the filter are also discussed.

21. R. Davidson, Interference Suppression, ELECTRICAL REVIEW, Vol. 157, pp. 755-758, Oct. 14, 1955.

    The impact of British regulations governing r-f suppression on small motors is discussed. The generation and propagation of RFI, methods of suppression, and safety aspects are reviewed.

22. R. S. Warner, W. P. Barrett, An Interference Suppression Capacitor Goes to 'L', Proceedings of the 2nd Conference on Radio Interference Reduction, Armour Research Foundation, March 1956.

23. H. J. Reich, Interference Suppression in A-M and F-M, COMMUNICATIONS, Vol. 22, pp. 7, 16, Aug. 1942.

    An analysis of interference suppression in a-m and f-m systems is presented. Interference from undesired carriers, interference in modulated and unmodulated carriers, and static interference are discussed.

24. B. Blank, Investigation and Study of Communication Interference Reduction Techniques, Georgia Tech, Final Rpt. Jan. 1958, (AD-148 844).

25. George E. Stannard, et al., Investigation of Solid-State Rectifier Devices as Radio Noise Suppression Components, Worchester Polytechnic Institute, Quarterly Prog. Rpt. No. 1, Aug. 1953, (AD-18 553; No. 2, Nov. 1953, (AD-22 861); No. 3, Feb. 1954, (AD-29 074); No. 4, May 1954, (AD-34 226); No. 5, Aug. 1954, (AD-44 395); No. 6, Nov. 1954, (AD-51 439); No. 7, Feb. 1955, (AD-58 372); and Final Rpt., June 1, 1953 to May 31, 1955, (AD-66 731).

The purpose of this series of reports was to investigate and determine the usefulness, applications, and limitations of non-linear devices, in particular dry disk rectifiers, in the suppression of RFI generated by current-interrupting contact points. The results of a library research and of laboratory experiments are reported. Suppression capacitors were also studied after it was found that non-linear devices, such as diodes, were ineffective in reducing RFI due to low voltage breakdown. The effects of suppressors on normal operation of the circuit were also investigated.

26. R. M. Janowiak, R. E. Saxe, Low Pass Filters Using Ferrites, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1958, pp. 475-486, (AD-234 212).

This report describes various physical configurations of ferrite materials that have been examined in an attempt to provide a compact low pass filter. The lossy characteristics of the ferrites are utilized to enhance the filter characteristics. The filters have power limitations because of saturation effects.

27. H. J. Blaine, Low Tension Magneto Filter--Radio Interference Attenuation Test Of, Office of Technical Services Pamphlet 97414, Dec. 1944.

"Results of tests to determine the amount of attenuation to the VHF ignition interference obtained (1) through the insertion of the sample filters in the switch and vibrator circuits and (2) with the type 154 flexible conduit installed on the switch and vibrator circuits."

28. R. S. Davidson, Measurement and Suppression of Radio-

Influence Voltage, ELECTRICAL MANUFACTURING, Vol. 40, pp. 79-81, Dec. 1947.

29. J. H. Evans, The Measurement and Suppression of Radio Interference, JOURNAL OF BRITISH INSTITUTE OF RADIO ENGINEERS, Vol. 9, pp. 46-59, Feb. 1949.

"The paper firstly outlines the nature of Radio Interference and the principles of measurement, goes on to describe measurement techniques as used by a manufacturer, and briefly reviews available methods of suppression and the difficulties encountered in their application. Finally, the paper considers recommended suppression limits and points out some anomalies caused by their specification."

30. Scott L. Shive, Measurement of Filter Insertion Loss at High and Ultra High Frequencies, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1328, Sept. 22, 1950.

This report discusses the fundamental principles of filter evaluation in terms of insertion loss measurement and points out the techniques and procedures evolved at the Laboratory by which accurate and meaningful data at ultra high frequencies can be obtained. The philosophy of some of the measurement concepts are indicated.

31. C. V. Aggers, Methods of Controlling Radio Interference, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 59, pp. 193-199, April 1940.

"This paper summarizes the recognized methods for reducing at the source man-made radio noises. The effectiveness of the different controlling methods is discussed in the light of efficiency and utility. The use of condenser filters and choke coils is so broad that this paper is confined to the more important applications of these controlling devices. Filters and coils are so important that specific applications are discussed in detail. The application of these devices to other apparatus is governed by the type, location, and use of the apparatus."

32. S. Charp, Miniature Radio-Interference Suppression Filters, Laboratories of Research and Development, Franklin Institute, Phila., Pa., Contract DA 36-039-sc-5521, Quarterly Engineering Rpts. No. 1, June 1951; No. 2 Sept. 1951; No. 3, Dec. 1951; No. 4, [illegible] 1952; Final Rpt. April [illegible], 1952, [illegible].

The basic principles for attenuation of noise in circuits are reviewed in the first report. Materials applicable to these principles are also discussed. The second report covers the use of powdered iron as a medium in which filter elements are immersed. Attempts were made to measure skin effect of conductors in dissipative filtering. The effects of ferrite materials around coils in filters were also investigated. The third and fifth reports continue with studies on ferrite materials. It was found that filters using ferrite cores showed an appreciable drop in insertion loss under loaded conditions.

33. D. B. Wright, J. C. Senn, A. M. Brown, A. W. Gosley, NAVCERELAB Radio Interference Suppression of Operation DEEP FREEZE I Equipment, Naval Civil Engineering Research and Evaluation Laboratory, Tech. Memo M-115, Nov. 1, 1956.

"This report describes the types of interference sources encountered and discusses suppression techniques applied to certain Operation DEEPFREEZE I equipment (supplied) by NAVCERELAB. The suppressed equipment is catalogued, and presuppression and postsuppression conformance test data are presented and discussed." Pictures of suppression components are included. Test equipment and test conditions are also described.

34. L. H. Engel, New Cartridge Static Suppressor, SCIENCE, Vol. 88, pg. 8, Oct. 21, 1938.

35. Rod MacDonald, Noise Suppression in Mobile Equipment, QST, pg. 59, Sept. 1951.

The author suggests a simple method of locating and eliminating automobile ignition interference in a ham radio. The method consists of using a coaxial cable connected to the antenna terminals and using the free end as a probe in locating offending circuitry. Bonding or by-passing noisy circuits is suggested as the remedy.

36. Varone, One Point Ground System with R-F Shielding and Filtering, ELECTRICAL ENGINEERING, Vol. 79, pp. 1028-33, Dec. 1960.

37. F. N. Hansen, A Polarized Dissipative RFI Suppression Filter, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 473-477, Nov. 1961, (AD-276 205).

"A new filter is described, whereby series inductance and distributed shunt capacitance are combined with electrical loss in a compact device without the use of lumped parameter reactive components and without obtaining the undesirable peaks and valleys which usually characterize the attenuation performance of lumped parameter circuits when plotted in the frequency domain. The addition of a feed-through capacitor on one end acts to polarize this filter, thus obtaining desirable performance for noise suppression at a magnetron."

38. P. B. Wilson, Jr., Practical Approach to Interference Prediction and Suppression, ELECTRONICS, Vol. 33, pp. 84-87, Sept. 9, 1960.

This article presents step-by-step procedures for predicting interference that will be generated in a printed circuit card. Suppression techniques applied are separation of components and proper grounding and shielding. Filtering the entering point of power supplies is also considered.

39. Power Line Filters, Sprague Electric Co., North Adams, Mass., April 1953, (AD-14 908).

This report covers the development of a series of low-shock power line type radio noise filters for use in 125 and 250 volt, 60 cycle power systems. Attenuation of RFI in the frequency range of 150 kc to 156 mc was sought. M-derived and pi filters were given considerable study. The designs and the insertion loss characteristics of the final filters are presented.

40. H. R. Schwenk, Preventative Design Aspects of RFI Control, SPERRY ENGINEERING REVIEW, Vol. 11, pp. 15-22, Dec. 1958.

The author advocates consideration of RFI control from the beginning of a design project and lists seven sequential steps which, if followed throughout design will help insure a RFI-free product at the end. He describes the basic types of suppression devices and gives examples of how they can be applied to some common RFI sources.

41. John L. Pancoast, Qualification Tests of Filtron Radio Interference Filter Type FA-555B, Naval Engineering Experiment Station, Annapolis, Md., EES Rpt. No. 810033-P (2), March 20, 1956, (AD-208 941L).

42. H. R. Wallace, William Coquillettee, Radio Interference Can Be Reduced To Minimum by Grounding, Coupling, U. S. BUREAU OF SHIPS JOURNAL, Vol. 1, pp. 33-35, July 1952.

The authors point out that a good d.c. ground may be a very poor a.c. ground. Ground leads have been shown to be good radio frequency radiators. The value of cabinet shielding is stressed and examples of proper and improper cabinet construction are given.

43. Radio Interference Reduction, U. S. Army, AR 105-68, July 26, 1955.

44. R. A. Dilworth, Radio Interference. III. Suppression, POST OFFICE ELECTRICAL ENGINEER'S JOURNAL, Vol. 51, pp. 40-45, Pt. 1, April 1958.

45. R. H. Brook, 200° C Radio Interference Filter Program, Filtron Co., Inc., Flushing, N. Y., Interim Tech. Engineering Rpt. 1 on Phase 1, Dec. 1, 1958 to March 1, 1959, (AD-215 355); Interim Rpt. 2, March 1, 1959 to June 1, 1959, (AD-230 389), Interim Rpt. 3, June 1, 1959 to Sept. 1, 1959, (AD-229 371); Interim Rpt. 5, Dec. 1, 1959 to March 1, 1961, (AD-253 265).

"Efforts are concerned with the development of a series of filters for operation at 200° C and the establishment of a pilot production line. Preliminary electrical designs were formulated. These designs established the parameters required to provide 40-db attenuation at full rated load from 150 to 250 kc, and 60 db from 250 to 1000 mc. Preliminary mechanical filter designs were developed. These designs incorporate either teflon or ceramic dielectric connectors, ceramic terminals and completely welded containers. All internal connections are either mechanically fastened or spot welded. Torodial inductor cores were subjected to high temperature tests. Standard finish molybdenum permalloy cores deteriorated after extended periods at 200° C. However, a series of high temperature powdered iron cores withstood 200° C operation and had suitable saturation characteristics. A sample molybdenum permalloy core utilizing a special high temperature finish exhibited suitable characteristics. Capacitors were wound of .001-in. thick teflon film and .00075-in. mica paper and subjected to preliminary electrical tests. The teflon capacitors showed excellent characteristics."

46. Radio Interference Filters, U. S. BUREAU OF SHIPS

JOURNAL, Vol. 6, pp. 33-34, July 1957.

Typical circuits for four kinds of radio interference filters--low-pass, high-pass, band-pass, and band-elimination--are diagrammed.

47. H. O. Merriman, F. G. Nixon, Radio Interference--Investigation, Suppression and Control, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 27, pp. 16-21, Jan. 1939.

The work of the Radio Division of the Division of Transport of Canada in locating and controlling radio interference is described. General means of suppressing interference through the use of capacitors, choke coils, and shielding are outlined. Reference is also made to legal action taken in Canada to control the use of interfering apparatus. The problem of measurement standards is raised, and one system is given.

48. Radio-Interference Suppression, ELECTRICAL REVIEW, Vol. 145, pp. 759-760, Oct. 21, 1949.

49. S. F. Philpott, Radio Interference Suppression, ELECTRICIAN, Vol. 144, pp. 1025-1029, March 31, 1950.

"Obligations imposed upon manufacturers under the Wireless Telegraphy Act of 1949, lend topicality to this article by the Chief Electrical Engineer of Wolf Electric Tools, Ltd., through whose courtesy we are permitted to reproduce the photograph in Fig. 2. An expert on fractional horsepower motors, Mr. Philpott deals mainly herein with interference caused by such motors, but much of the information will be found of general application."

50. G. L. Stephens, Radio Interference Suppression, Iliffe and Sons, Ltd., London, 2nd Edition, 1952.

"Discusses origins of interference and basic principles of suppression techniques in radio and TV reception. Presents data on design and choice of suppressor components, methods of locating the source of interference, and suppression at the receiver itself."

51. Whitfield C. Smith, Radio Interference Suppression, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON COMMUNICATIONS SYSTEMS, Vol. CS3, pp. 8-13, March 1955.

Radio interference is defined and its effect on a receiver is discussed. Sources of RFI are listed.

Shielding and other types of suppression, including resistors, by-pass capacitors, coaxial capacitors, and filters are discussed. Gasketing and bonding are also mentioned.

52. D. B. Wright, Radio Interference Suppression as Applied to Deepfreeze Equipment, Naval Civil Engineering Research and Evaluation Lab., Tech. Note TN-256A, Sept.-Oct. 1955.

This publication consists of 18 instruction manuals telling how to apply various suppression techniques to pieces of equipment to be used in Operation Deepfreeze.

53. Radio-Interference Suppression as Applied to Experimental Engines, Model B, BP, BPK, and BR-6, Manufactured by Briggs and Stratton, Corp., U. S. Army Signal Corps, Engr. Memo D-293-E-P-45, 1945 (PB 15 238).

54. George William Ingram, Radio Interference Suppression as Applied to Radio and Television Reception, 2nd Edition.

55. S. L. Shive, Radio Interference Suppression Characteristics of Various Capacitor Types, Coles Signal Laboratories, April 1950, (ATI 76 857).

56. Radio Interference Suppression of a Prosperity No. 2C-JR Laundry Washer, Naval Civil Engineering Lab., Feb. 1953, (PB-154 651).

57. L. J. Chapman, Radio Interference Suppression of Electric Motor Unit, Manufactured by the Silver Creek Co., Silver Creek, N. Y., Signal Corps Engineering Lab., March 1947, (PB-L-78 706).

58. T. J. Kalafarski, Radio Interference Suppression System Conforming to Military Specification MIL-S-11683 -- Briggs and Stratton Gasoline Engines Models N, 6, 8, 9, 14. and 23, Coles Signal Lab., Fort Monmouth, N. J., Tech. Memo M-1487, Feb. 20, 1953, (AD-14 142).

Shielding and bonding principles are applied to this system. Shielding terminations are designed to be compatible with normal production procedures. The system is described and drawings are included.

59. Hyman Goldman, William Endlicher, Radio Interference Suppression System, Electric Machinery 30-KW 3-Phase Alternator, Coles Signal Lab., Fort Monmouth, N. J., Tech. Memo M-1566, March 4, 1954, (AD-30 709).

A simpler suppression system than previously used

is described in this report. Four feed-through capacitors and proper seating of brushes eliminated 17 by-pass capacitors, seven shielded d-c leads, and numerous bonding applications.

60. Howard E. Hennell, Radio Interference Suppression System, for a Model 305 ACK-99E 3.5 KW/AC. 1.5 KW/DC Engine Generator Manufactured by D. W. Onon and Sons, Inc., Minneapolis, Minn., Army Signal Engineering Lab., Fort Monmouth, N. J., Tech. Memo M-1853, Jan. 22, 1958, (AD-156 256).

"The radio suppression system was evaluated for conformance with MIL-I-11683A. Tests for radiated interference were conducted between 0.15 and 40.0 mc with test set AN/URM-3 and between 40.0 and 1000.0 mc with test set AN/URM-29. Conduction tests were made between 1.5 to 40.0 mc at the generator output terminals with test set URM-3 and coupling blocks CU-152 and CU-153. Results showed that the radio interference suppression system was unsatisfactory because objectionable radiated and conducted interference emanated from the 30-v dc generator between 5.0 and 20.0 mc; this interference was attenuated to the specified level."

61. B. Hoerl, Radio Interference Suppression System for a Model 4820 30 KW Generator Set, Manufactured by Electric Service Engineering Co., Lockport, Ill., Army Signal Corps Lab., Nov. 1956, (AD-119 377).

62. John Lucyk, Radio Interference Suppression System for a Model PU-20/C Motor Generator Set Manufactured by Bogue Electric Manufacturing Co., Paterson, N. J., Army Signal Engineering Lab., Fort Monmouth, N. J., Tech Memo M-1845, Dec. 10, 1956, (AD-125 160).

"The radio interference suppression system proposed by the contractor was found to be unsatisfactory as objectionable radiated and conducted interference was found to be emanating from the unit in the frequency range of 20.0 to 95.0 megacycles. This interference was attenuated to the level specified in the governing specification by the engineers conducting the investigation and the final suppression system is described. The permissible limits of interference and the test procedure are detailed."

63. H. E. Hennell, Radio Interference Suppression System for a Model WD-23 Vacuum Cleaner Manufactured by the Clarke Sanding Machine Co., Muskogan, Mich., Army Signal Corps Lab., Oct. 1956, (AD-113 390).

64. G. Mitchell, Radio Interference Suppression System for Atlantic Equipment Company Model DAW - 100 KW Generator Set, Army Signal Engineering Laboratories, July 1956, (AD-105 419).

65. E. Wimmer, Radio Interference System for Barber-Greene Company Model 879A Bituminous Material Machine, Army Signal Engineering Laboratories, May 1956, (AD-105 416).

66. R. R. Newcomb, Radio Interference Suppression System for Bay City Shovel Model 180M Truck-mounted Crane-shovel, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Tech. Memo M-1891, May 24, 1957, (AD-138 468).

"The crane was investigated for conformance to Spec MIL-I-11683A for radio interference suppression. Data are presented to assist in the maintenance and rebuilding of the suppression units. Tests for radiated interference were conducted over the 0.15 to 40.0 mc range with test set AN/URM-3 and over the 40 to 1000 mc range utilizing test set AN/URM-29. The permissible levels of interference are indicated. Results indicate that the suppression system when properly applied will attenuate radiated interference to the degree required."

67. Hyman Goldman, Radio Interference Suppression System for Black and Decker Company Catalog No. 590E 7-inch Sander Grinder and Catalog No. 361E ½-inch Standard Drill, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1628, Feb. 24, 1955, (AD-65 842).

The suppression system, consisting of by-pass capacitors from the brushes to ground and by-pass capacitors from each side of the input line to ground, is described. Two photographs are included.

68. B. Hoerl, Radio Interference Suppression System for Carter Motor Co. Model E642P Dynamotor, Army Signal Corps Engineering Laboratories, Oct. 1955, (AD-78 089).

69. J. Lucyk, Radio Interference Suppression System for Caterpillar Tractor Co. Model D 2 Tractor, Army Signal Corps Engineering Laboratories, Feb. 1956, (AD-95 845).

70. Hyman Goldman, Radio Interference Suppression System for Chrysler Corporation Engine Model IND-8-54 as Utilized on Hale Fire Pump Company Type CFS 500 GPM Fire Fighting Pumper, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1626, Feb. 24, 1955, (AD-65 803).

The suppression system as applied to the ignition

and battery charging systems is described. Shielding and bonding principles and feed-through capacitors are used. Drawings are included.

71. E. Wimmer, Radio Interference Suppression System for Clark Equipment Company Model 75 AG Front End Bucket Loader, Army Signal Corps Engineering Laboratories, July 1956, (AD-105 418).

72. R. C. Hizer, Radio Suppression System for Cleaver Brooks Company--Model DVC-8M Distillation Unit, Army Signal Corps Engineering Laboratories, July 1956, (AD-111 335).

73. E. Wimmer, Radio Interference Suppression System for Clemente Manufacturing Co. Model G-10 Hand Type Vacuum Cleaner, Army Signal Corps Engineering Laboratories, July 1956, (AD-106 083).

74. T. J. Kalafarski, Radio Interference Suppression System for Continental Model R-602 Gasoline Engine as Utilized on Hale Fire Pump Company Model 20 FG-2 Fire Foam Generator, Coles Signal Laboratory, Fort Monmouth, N. J. Tech. Memo M-1643, April 13, 1955, (AD-65 801).

Potential sources of RFI are listed and the measures taken to suppress RFI are enumerated. Drawings are included.

75. John Boyadjian, Radio Interference Suppression System for Continental Model R-602 Gasoline Engine as Utilized on John Reiner and Company Model GP-110-3 Centrifugal Pump, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1660, May 27, 1955, (AD-66 359).

The use of bonding, shielding, and feed-through capacitors in the suppression systems on the ignition and battery charging systems is described. Pictures and diagrams are included.

76. G. Mitchell, Radio Interference Suppression System for Crouse-Hinds Company 18" Shuttered, Incandescent, Lamp-type Searchlight, Army Signal Corps Engineering Laboratories, March 1956, (AD-96 032).

77. G. Mitchell, Radio Interference Suppression System for Cummins Engine Company Model HF 45 D, 45 KW, 400 cycle Engine Generator, Army Signal Corps Engineering Laboratories, June 1955, (AD-74 637).

78. R. C. Hizer, Radio Interference Suppression System for E. D. Etnyre Bituminous Material Distributor, Army Signal Engineering Laboratories, Fort Monmouth, N. J. Tech.

Memo M-1898, June 25, 1957, (AD-138 470).

"The conformance of model MX, style RE distributor to Spec MIL-I-11683A for interference suppression was investigated. The model MX is a trailer mounted, 1250-gal. capacity distributor powered by a 4-cylinder, 4-c, water-cooled, standardized Hercules model IXB3-ER engine rated at 20 hp for 1200 rpm. Tests for radiated interference were conducted over the 0.15- to 40.0-mc range with the AN/URM-3 set and the 40.0- to 1000.0-mc range with AN/URM-29 set. The test results indicated that the radio interference suppression system, when properly applied, will attenuate radiated and conducted interference to the degree required by the specification."

79. F. Alvarez, Radio Interference Suppression Systems for Electric Motor Driven Tools Utilized by the Department of the Army, Army Signal Engineering Laboratories, April 1957, (AD-145 225).

80. Albert Ruzgis, Radio Interference Suppression Systems for Electrical Sub-Assemblies of Tank, T-92, Army Signal Engineering Laboratories, Fort Monmouth, N. J. Tech. Memo M-1911, Aug. 28, 1957, (AD-145 348).

"The following assemblies to be utilized in the T-92 tank were modified to suppress radio interference and then tested: (1) auxiliary engine generator, (2) driver compartment ventilating fan, (3) turret blower, (4) personnel heater, (5) slip ring junction box, (6) radio junction box, and (7) ammunition booster motors. Tests for radiated interference were conducted from 0.15 to 40.0 mc by utilizing test set AN/URM-3 and from 40.0 to 1000.0 mc, with test set AN/URM-29. The antenna of the test equipment was located 12 in. from the components during all measurements as required by Spec. MIL-S-10379A. Conduction tests were performed over the 1.5- to 40.0-mc range at the output terminals of the auxiliary engine generator and at power input leads of each of the other sub-assemblies by utilizing test set AN/URM-3 and coupling blocks CU-152 and -153. Test results indicated that the radio interference suppression modifications on the sub-assemblies will satisfactorily attenuate radiated and conducted interference in conformance with Spec. MIL-S-10379A."

81. R. Hizer, Radio Interference Suppression System for Federal Sign and Signal Corp. 6, 12, and 24 volt Sirens,

Army Signal Corps Engineering Laboratories, June 1956, (AD-105 417).

82. R. Hizer, Radio Interference Suppression System for Four Wheel Drive Auto Co. Model FR50T Fire Truck, Army Signal Corps Engineering Laboratories, May 1956, (AD-100 121).

83. E. Wimmer, Radio Interference Suppression System for GAR Wood Industries Inc., Model 75B Crawler Mounted Crane, Army Signal Corps Engineering Laboratories, July 1956, (AD-106 084).

84. B. H. Hoerl, Radio Interference Suppression System for General Motors Corporation Diesel Engine Models 6058C and 4030C as Utilized on Insley Manufacturing Corporation Model WB-9555 Crane, Coles Signal Laboratory, Fort Monmouth, N. J. Tech. Memo M-1627, Feb. 28, 1955.

Bonding and shielding principles and feed-through capacitors were used in the system described herein. Even the windshield wipers were found to be a source of interference. Drawings are included.

85. Fred B. Alvarez, Radio Interference Suppression Systems for Heaters Utilized by the Department of the Army, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Tech. Memo M-1854, Jan. 28, 1957, (AD-125 734).

"A radio interference suppression system is described which when properly applied will attenuate radiated interference to the degree required for conformance to the applicable suppression specifications which were considered. Recommendation was made that the material contained in the manual entitled "Suppression Systems Suggestions-Inspectors' Guide" be utilized as a reference in the application and inspection of the suppression systems applied to the units."

86. A. G. Ruzgis, Radio Interference Suppression System for Hercules QXLDER Gasoline Engine as Utilized on Kershaw Manufacturing Company Model 3FW-A Track Patrol, Ballast Regulator, Scarifier, and Plow, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1654, May 17, 1955, (AD-66 358).

The components of the battery charging system and ignition system to which suppression techniques were applied are described. Test procedures and permissible levels of radiation are given along with diagrams.

87. J. Boyadjian, Radio Interference Suppression System for Hercules Models TDXC and JXLDER Gasoline Engines as Utilized on Bay City Shovels, Inc., Model 150M Truck Mounted Crane, Coles Signal Laboratory, April 1955, (AD-66 267).

88. J. Lucyk, Radio Interference Suppression System for Hobart Brothers Company Model HF 30 GM, 30 KW, 400 cycle Engine Generator Set, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1638, April 5, 1955, (AD-66 813).

The potential sources of radio interference are listed and the preventive steps taken are listed. Drawings are included.

89. H. Goldman, Radio Interference Suppression System for Homelite Corp. Model 24D28-9 Engine Generator Set, Army Signal Corps Engineering Laboratories, Sept. 1956, (AD-113 387).

90. F. B. Alvarez, Radio Interference Suppression System for Huber Warco Manufacturing Co. 10-ton Road Roller, Army Signal Corps Engineering Laboratories, March 1956, (AD-95 849).

91. F. Alvarez, Radio Interference Suppression System for Ideal Electric and Manufacturing Co. Model S. O. 202060-062 Motor Generator Set, Army Signal Corps Engineering Laboratories, Jan. 1956, (AD-90 767).

92. J. Lucyk, Radio Interference Suppression System for Induction Soldering Equipment TL-615/U Manufactured by Marion Instrument Company, Manchester, N. H., Army Signal Corps Engineering Laboratories, Sept. 1956, (AD-113 388).

93. Hyman Goldman, Radio Interference Suppression System for John Reiner and Company Model GGC-10 AC, 10 KW Engine Generator, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1624, Feb. 15, 1955, (AD-61 560).

The suppression system as applied to the ignition system, battery charging system, alternator and exciter, control panel, and heaters is described. Drawings are included.

94. Robert C. Hizer, Radio Interference Suppression System for Kiekhaefer Aeromarine Motors Inc. Model KB6-F Gasoline Engine, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1489, April 1, 1953, (AD-12 465).

The originally designed suppression system did not

meet the requirements of MIL-I-11683, but the new system, which does meet the standard, is described. Bonding, shielding, and resistive leads were used.

95. J. C. Dockendorf, Radio Interference Suppression System for Mars Signal Light Company Model S60 Siren, Coles Signal Laboratory, Fort Monmouth, N. J., May 1955, (AD-69 652).

96. R. C. Hizer, Radio Interference Suppression System for Massey-Harris-Ferguson, Inc. Model I-244G Tractor, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Tech. Memo M-1899, June 26, 1957, (AD-138 561).

"The tractor was investigated for conformance to Spec MIL-I-11683A for radio interference suppression. Tests for radiated interference were conducted over the 0.15- to 40-mc and 40- to 1000-mc ranges with the AN/URM-3 and URM-29 test sets, respectively. Permissible levels of interference are given. When properly applied, the suppression system will attenuate radiated interference to the degree required."

97. R. C. Hizer, Radio Interference Suppression System for Model 422 AW "Speed Swing" Industrial Tractor Manufactured by the Pettibone Mulliken Corporation, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Tech. Memo M-1878, April 9, 1957, (AD-132 953).

"The radio interference suppression system proposed by the contractor was found to be satisfactory as no objectionable radiated interference was emanating from the unit. The final suppression system is described. The permissible levels of interference and the test procedure are detailed."

98. Emil V. Wimmer, Radio Interference Suppression System for Model 3462, 500 GPM Water Pump Manufactured by the Gorman-Rupp Company, Mansfield, Ohio, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Tech. Memo M-1912, Aug. 20, 1957, (AD-145 349).

"Radio interference tests were conducted on a 500-gpm model 3462-BS water pump which had been modified to suppress radio interference. This Gorman-Rupp centrifugal self-priming pump has a 4-in. inlet and outlet; it is powered by a Wisconsin model MVG4D, 4-cylinder gasoline engine (34.5 hp at 2200 rpm) equipped with a 24-v battery starting and charging system with magneto ignition. Following modification of the Wisconsin model MVG4D engine ignition

system and the 24-v charging system, tests for radiated interference were conducted over the 0.15- to 40.0-mc range by utilizing test set AN/URM-3 and from 40.0 to 1000.0 mc with test set AN/URM-29. The antenna of the test equipment was located 5 ft from the unit as required by Spec MIL-I-11683A. Test results indicated that the radio interference suppression system incorporated into the pump will satisfactorily attenuate radiated and conducted interference to the degree required for conformance to Spec MIL-I-11683A."

99. R. Newcomb, Radio Interference Suppression System for Models 22-240 and 22-241 Cleaners (Vacuum/blower) Manufactured by Ideal Industries, Army Signal Research and Development Laboratory, Fort Monmouth, N. J., April 1958, (AD-200 351).

100. R. Newcomb, Radio Interference System for Oshkosh Motor Truck Inc. Model W-700-15-R Snow Plow Truck Chassis, Army Signal Corps Engineering Laboratories, Fort Monmouth, N. J., July 1956, (AD-106 082).

101. R. C. Hizer, Radio Interference Suppression System for Power Unit PE-75 ( ), Coles Signal Laboratory, Fort Monmouth, N. J. Tech. Memo M-1552, Dec. 28, 1953, (AD-27 511).

A comparison of the effectiveness of a new suppression system with that of a system designed in 1944 is made. The new system is described and makes use of the principles of shielding and bonding and also utilizes feed-through capacitors.

102. J. Boyadjian, Radio Interference Suppression System for Waukesha Model 1456KB and 6SRKR Gasoline Engine as Utilized on Bay City Shovel, Inc. Model 180 M Truck Mounted Crane, Coles Signal Laboratory, Fort Monmouth, N. J., April 1955, (AD-64 625).

103. Theodore J. Kalafarski, Radio Interference Suppression System for Wisconsin Motor Corporation Gasoline Engines Models ABN, AKN, AEN, AEH, AFH, AGH, AHH, TE, MTFD, VE4, TF, VF4, VP4, MVE4D and MVF4D, Coles Signal Laboratory, Fort Monmouth, N. J., Tech. Memo M-1594, July 15, 1954, (AD-40 511).

Radio interference suppression systems conforming to the requirements of Military Specification MIL-I-11683A are described, and permissible limits of interference and test procedures are outlined. Suppression techniques include shielded and suppressed

spark plugs, shielded magneto, shielded ignition cable, magneto bonded to engine gear case, and shielded magneto switches.

104. A. Ruzgis, Radio Interference Suppression System for Worthington Mower Model G - Tractor, Army Signal Corps Engineering Laboratories, Oct. 1955, (AD-95 842).

105. H. Goldman, Radio Interference Suppression System for York-Shipley, Inc. High Pressure Steam Boiler, Army Signal Corps Engineering Laboratories, April 1956, (AD-96 036).

106. Radio Interference Suppressors, Sprague Electric Company, Contract AF 33(038)9353, Progress reports (2) April 13 to July 13, 1950; (3) July 13 to Oct. 13, 1950; (5) Jan. 13 to April 13, 1951; (8) Oct. 13, 1951 to Jan. 13, 1952; Final Report No. 1, Oct. 1952, (AD-18 101).

In this series of reports the theoretical development of various filters is extended to include lattice, m-derived, unsymmetrical and multi-mesh pi filters in addition to the single mesh pi filter. Models were made and measured to confirm the theoretical work. In higher frequency spectrum it was necessary to carefully control capacitor design, shielding the common impedance. The filters are for a-c and d-c power line applications. In report #3, the theoretical work is described for "L" sections. The problem of size and weight of inductors is considered and schemes for cancellation of saturating field in ferromagnetic cores are examined. In report #5, the design of 11 filters and production problems are discussed. Curves of insertion loss versus frequency for two 500 ampere 28 volt d-c filters are given. Report #8 describes production tests on previously designed filters and new designs are listed. Insertion loss versus frequency curves are presented for completed filters. The final report no. 1 gives a summary of results to that time.

107. Radio Interference Suppressors, Sprague Electric Company, Contract AF 33(038)9353, Progress Reports (10) April 24 to July 24, 1953, (AD-22 904); (11) July 24 to Oct. 24, 1953, (AD-42 387); (12) Oct. 24, 1953 to Jan. 24, 1954, (AD-42 388); Final Report, Oct. 1954, (AD-50 997).

In an extended phase of the contract described in the previous reference, investigation is made of the use of resin impregnated metallized paper in 125° C suppressors. New developments in the field of magnetic core materials are investigated to

determine if low frequency suppressors can be reduced in size and weight. New dielectric materials are investigated for 200° C and higher applications. A summary of all results is given in the final report.

108. C. W. Frick, S. W. Zimmerman, Radio Noise Filters Applied to Aircraft, ELECTRICAL ENGINEERING, Vol. 62, pp. 590-595, Sept. 1943.

This paper deals with capacitor and filter type suppressors. Typical characteristics for some filter suppressors are given. Physical separation and shielding are treated briefly. Methods for measuring the effectiveness of suppressors are suggested.

109. Radio Noise Suppression Units for Aerial Photographic Equipment, U. S. Army Air Forces, TSEPL-4-675-149-2, 1944, (PB-5 768).

110. Don Miller, Radio Noise Suppressors, U. S. Army Air Forces, Engineering Division, ENG-59-675-149-1, 1944, (PB-11 639).

111. A. M. Intrator, Recommended Techniques for the Suppression of Radio Interference from Engine Generator Sets, Naval Civil Engineering Research and Evaluation Laboratory, Tech. Memo M-072, Aug. 28, 1952.

Common sources of RFI are listed and the general suppression technique applicable to each is listed. Shielding, bonding, use of by-pass capacitors, and distributed resistance leads are proposed.

112. Ida, Reducing Electrical Interference, CONTROL ENGINEERING, Vol. 9, pp. 107-111, Feb. 1962.

"After discussing several types of interference that can and do degrade process instrument performance, the author shows how to get cleaner control signals by proper use of shielding, by avoiding ground loops, and by balancing of transmission lines."

113. D. L. Sullivan, Relay Noise Suppression in Airborne Electronic Systems, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, pp. 644-662, Oct. 1959, (AD-235 099).

"Techniques for transient noise suppression of relays and similar inductive circuits are presented

from a systems viewpoint. The effect of pickup and coupling on cable routing is discussed, as are methods of obtaining suppression with emphasis on early design level planning."

114. Report of Radio Interference Tests of LVT-IV Polar Fire Fighting Vehicle, Naval Civil Engineering Laboratory, Port Hueneme, Calif., April 1956, (AD-108 358).

115. Joseph Allen, R-F DC Insertion Loss Measurements of Radio Interference Filters, Army Signal Engineering Laboratories, Fort Monmouth, N. J., Test Rpt. T-1413, Nov. 7, 1956, (AD-125 158).

"Tests showed that the application of rated current may cause considerable variations in the no-load insertion-loss measurement of radio-interference filters. These variations usually represent a decrease in insertion loss at the lower test frequencies or a decrease in the suppression effectiveness of filters. The insertion loss of filters employing solenoidal chokes as inductance elements were unaffected by the application of rated current; only a fourth of the randomly selected filter samples tested utilized such nonsaturable inductance elements. To obtain a realistic evaluation of the suppression effectiveness of radio interference filters, it is necessary to conduct insertion-loss tests with rated load current applied. The test methods and equipment utilized for these tests provide an accurate method of performing insertion-loss measurements with rated load applied."

116. RFI: Suppression Methods for Water Heating Plants, ELECTRICIAN, Vol. 116, pg. 96, June 24, 1936.

117. D. J. Jobe, Shipboard Electronic and Electrical Installation Methods for Reduction of Electrical Interference, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, pp. 35-40, Dec. 7-8, 1954, (AD-76 686).

"Electronic and electrical equipment installation methods effectively used by a naval shipyard for interference reduction are outlined. The value of grounding and bonding for interference reduction has been over-emphasized. Ship electronic and electrical installation plans are being revised to be more specific on what, where, and how to bond for effectiveness. Interference may be reduced by improving the shielding of equipment and cables, and

isolating certain units, cables, and antennas. Filtering has been one of the most effective interference reduction measures used by the Navy. Detailed installation plans, good workmanship, correct alignment and adjustment, and good maintenance of electronic and electrical equipment aboard ship is of paramount importance in reducing interference."

118. W. Pecota, Small, Lightweight R-F Interference Suppressors Using Transistors, INSTITUTE OF RADIO ENGINEERS NATIONAL CONVENTION RECORD, Pt. 8, Vol. 6, pp. 164-175, 1958.

"A conventional filter designed to suppress relay coil and heater thermostat switches often presents unsurmountable weight and packaging difficulties. RFI filters using only a transistor and a resistor may be used to replace conventional types in direct current circuits, thus reducing filter weight to less than five per cent and eliminating shielding, special wire routing, and filter mounting and space problems. Successful design of a transistor filter requires matching of load, switch, and transistor characteristics heretofore not considered by the filter design engineer. A complete picture of the effects of alpha-cutoff, carrier diffusion, contact potential, voltage, current, and load impedance on the amount of RFI suppression obtained with a transistor filter is presented."

119. M. E. Krom, Suppressing High-Frequency Disturbances from Telephone Apparatus, BELL LABORATORIES RECORD, Vol. 20, pp. 254-257, June 1942.

"Discusses the use of special filters designed to suppress noise from switching and commutating devices. These filters are described. Methods of connecting these filters are prescribed since their effectiveness depends on the manner in which they are connected to the circuit."

120. D. C. Rogers, Suppressing Impulse Noise, WIRELESS WORLD, Vol. 55, pp. 489-492, Dec. 1949.

121. Suppression Applied to Outboard Motor, Model POLR-15, (Johnson Motors Division, Outboard Marine and Manufacturing Co.), U. S. Army Signal Corps, Engr. Memo D-363-E-P-45, 1945, (PB-15 236).

122. S. L. Shive, Suppression Capacitors, Proceedings of the Conference on Radio Interference Reduction, Armour

Research Foundation, pp. 305-317, Dec. 1954, (AD-76 686).

The development of suppression capacitors is reviewed with respect to the increasing RF spectrum. The principle of the use of suppression capacitors is outlined, and various types of capacitors are discussed. Particular attention is focused on feed-through capacitors. The author also points out the limitations on the use of capacitor suppressors.

123. Hyman Schwartz, Suppression Investigation of Jack and Heintz G-22 300 Ampere DC Generator for Armored Vehicles, Coles Signal Laboratory, Fort Monmouth, N. J., Test Rpt. T-1334, June 10, 1954, (AD-36 481).

The suppression system for this equipment, designed by the laboratory personnel, is described. The principles of shielding and bonding and feed-through capacitors are used. Drawings and pictures are included.

124. A. Hunter, Suppression of Electrical Interference to High-Frequency Apparatus in Naval Vessels, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, Pt. 3 (Radio and Communication Engineering), Vol. 96, pp. 159-165, March 1949.

"The paper is a review of the special problem of the suppression of interference from electrical equipment in naval craft. The paper deals for the most part with only the smaller vessels since the problem is very much reduced in steel decked ships. The relative importance of the alternative methods of eliminating interference, namely screening and suppression at source, are discussed, and it is concluded that suppression at source is more certain and durable. Details are given of the design and performance of the suppression equipment in use at the end of the war. The development of suitable components to withstand the rigors of naval service is also described, with particular reference to capacitors. There are brief references to interference measurement and to the instruments employed."

125. Suppression of Interference, ELECTRICAL TIMES, Vol. 127, pg. 411, March 10, 1955.

126. Suppression of Power Generating Unit HRUA, 1.5 kw Engine Generator, U. S. Army Signal Corps, Engr. Memo D-57-E-P-46, 1945, (PB-9 608).

127. Suppression of Radiation Interference, ELECTRONIC

ENGINEERING, Vol. 22, pg.362, Sept. 1950.

This article reports on the successful application of a quick-drying water-based conductive paint to the inside of a TV cabinet in an effort to reduce interference to normal radio reception by television receivers.

128. Suppression of Radio Interference, ELECTRICIAN, Vol. 143, pg. 1235, Oct. 14, 1949.

129. Suppression of Radio Interference Created by Engine-Generator Units, U. S. Army Signal Corps, Manual SIG 461-1, Aug. 1945, (PB-19 223).

130. Suppression of Radio Noises, U. S. War Department, Tech. Manual TM-11-483, (PB-3 137).

131. H. W. West, Suppressor Unit Capacity Selector, RADIO NEWS, Vol. 38, pg. 88, April 1945.

132. A. M. Brogden, J. C. Cook, C. F. Douds, A Survey of Interference Reduction Techniques, Vol. 1, Communication and Radio, HRB-Singer, Inc., State College, Pa., June 1962, (AD-277 558).

133. Trolley Busses; Methods of Suppressing Radio Interference, ELECTRICIAN, Vol. 116, pg. 482, April 10, 1936.

134. Vehicle Design Considerations to Meet Suppression Objectives, Society of American Engineers Paper 315 C, March 13-17, 1961.

CHAPTER XII

RADIO FREQUENCY INTERFERENCE MEASURING DEVICES

Radio interference, for purposes of measuring, can be broken into two broad categories. Narrow band interference originates at a discrete frequency or narrow group of discrete frequencies. This is typified by spurious emissions from transmitters, receiver local oscillator emissions and so on. The other category, broad band interference, generally includes impulsive type noise and random noise. Examples of this are transients from switching relays, ignition systems, radar pulses, etc. Since narrow and broadband interference have distinctive characteristics the question then is, "What shall we measure?". For instance the susceptibility of receiver circuits to broadband interference is a function of the bandwidth of the circuit. Therefore it would seem desirable to measure broadband interference in terms of the bandwidth factor. Of the three measurable voltage parameters, peak, rms and average, only peak and rms are functions of bandwidth for both impulse and random noise. With a low repetition rate the rms value, or average power, falls to a low level. Therefore the peak parameter is best for measuring broadband interference. The problem of measuring various forms of interference was commented on by Burrell, in ref. (27), in 1941. He writes,

> The most difficult problem in radio noise measurement is to select, from the many types of measure-

ments which might be made, the ones which are the most significant for the purposes desired. It is easy to obtain numerical measures of radio noise; the problem is the interpretation of the values after they are obtained.

A typical RIFI meter is shown below from an illustration contained in ref. (36), a discussion of RFI instrumentation.

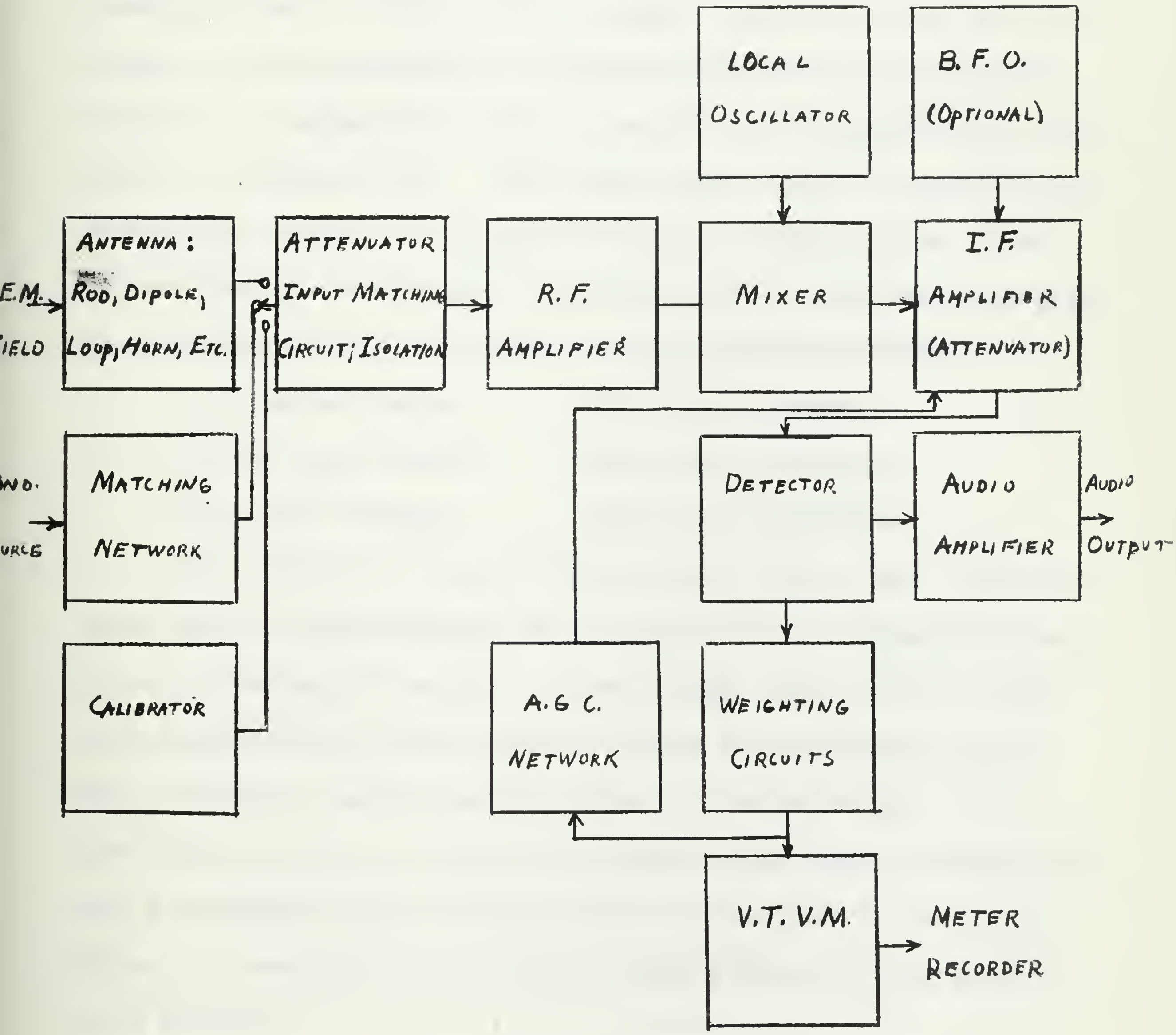

Fig. XII - 1 Block Diagram of a Typical RIFI Meter

The instrument is basically a superhetrodyne receiver containing an r-f mixer, oscillator, and i-f amplifiers. In addition attenuators (usually in 10 db steps), output indicators (meter, oscilloscope, or recorder) and means of internally calibrating the device are included. The detector circuit is usually designed so that three different voltage functions may be taken. The average function gives the average of the envelope of the waveform at the i-f amplifier output. To accomplish this a long RC time constant for averaging is incorporated. The quasi-peak function measures the "nuisance" value of the interference. There are no fixed values for the weighting circuits in the quasi-peak position. The following time constants are most commonly found:

(1) 1 msec charge	600 msec discharge
(2) 10 msec charge	600 msec discharge
(3) 1 msec charge	160 msec discharge

In a series of tests in the early 1940's, the effect of each type of interference on a signal being listened to was given a "nuisance" value. It was found that the 10 - 600 time constant had the greatest degree of correlation with the "nuisance" value for all types of interference. The peak function has a very short charge time (one microsecond) and a discharge time in the order of a second. The output meter is then able to read peak values even for low repetition rates.

Internal calibration of the RFI meter is usually

accomplished by one or a combination of the following: a sine wave oscillator--tuned or fixed frequency; a random gaussian noise generator; and an impulse generator. Impulses are usually generated by periodically discharging a pulse forming transmission line resulting in a rectangular pulse output whose amplitude is one-half the charging voltage. The frequency spectrum for such a pulse is

$$F(f) = 2A\tau \frac{\sin \pi f \tau}{\pi f \tau}$$

where $F(f)$ = spectral density in volts/cps

f = frequency in cps

At low frequencies $\frac{\sin \pi f \tau}{\pi f \tau} \cong 1$ and therefore the spectral density and the impulse strength are nearly equal.

Random noise generators are usually temperature limited diodes, the noise output being given by

$$i_n^2 = 2eIB_p$$

i_n^2 = mean-square noise current in bandwidth B_p

e = charge of the electron in coulombs

I = d.c. flowing between anode and cathode in amperes

B_p = effective bandwidth of the measuring circuit in cps.

These two types of calibrators, being broadband, have the advantage of their output being available anywhere in the band.

Since RFI meters must cover a wide spectrum of frequencies, various antenna forms are utilized. At the lower frequencies (below 30 Mc) vertical rod and loop antennas are used. The loop is usually insulated so that it may be used

as a probe in the vicinity of high voltages. From 30 to 1000 mc tuned dipoles are used and beyond 1 kmc calibrated horns are normally used.

In addition to measuring radiated interference the RFI meter is also used to measure conducted interference. Direct connection can be made through a coupling network that isolates the meter and maintains the proper impedance.

An excellent summary of the characteristics of commercially available RFI meters is included in ref. (36), an instrumentation article by Haber and Showers, and is reproduced in Fig. XII - 2.

The RFI meters described in Fig. XII - 2 record interference in terms of microvolts/meter or microvolts/meter/unit of bandwidth. It has been found desirable, particularly in areas where r-f hazards exist, to measure the r-f power density directly. Knapp and Lambdin, in ref. (34), describe such a device that uses constant gain antenna probes and a thermistor balanced bridge which will read power levels from 0.1 milliwatt to 2 watts over the frequency range of 200 mc to 10,000 mc. Although the instrument reads average power, the peak power of pulse interference can be quickly calculated if the duty cycle of the pulse transmission is known.

A different approach to measuring interference is described by Newman and Stahlman in ref. (10), a report on a counter-type interference analyzer. The counter analyzer

Fig. XII - 2

CHARACTERISTICS OF SEVERAL COMMERCIALLY AVAILABLE RIFI METERS

Manufacturer	Type Designation		Frequency Range	Bandwidth 6db(5)	Sensitivity limit(6)	Detector Function(7)	Calibrator Source	Pick-up Devices
	Commercial	Military						
Empire Devices	NF-105		0.014-1000mc/s with 5 tuning units as follows T-X/NF-105 14kc-150kc	600-1000cps(3)			variable prf impulse generator;	
			TA/NF-105 150kc/s-30mc/s	5-15kc/s(4)	1μv			loop, 12"; rod, 1/2 meter
			T-1/NF-105 20mc/s-200mc/s	100kc/s(3)	10μv			
			T-2/NF-105 200-400mc/s	200kc/s(3)	10μv	A P SBP	fixed frequency sine wave generator	tuned dipole, Broadband conical
			T-3/NF-105 400-100mc/s	300kc/s	10μv			
Empire Devices	NF-112		1-10kmc/s with 4 tuning units as follows T-1/NF-112, 1-2kmc/s	1mc/s and 5mc/s(3)	10μv	A P SBP	impulse generator 1000pps	Horns
			T-2/NF-112, 2-4kmc/s					
			T-3/NF-112, 4-7kmc/s					
			T-4/NF-112, 7-10kmc/s					
Ferris	32B		150kc/s-350kc/s, 550kc/s-20mc/s	10kc/s(3)	1/2μv	QP2	random noise generator	1/2 meter rod, inductive probe
Ferris	32D		550kc/s-25mc/s	6.4-9.6kc/s(2)	1μv	QP1 SBP	multi-vibrator	1/2 meter rod; loops: one per band 5"-6 1/2" "Square"; loop probe 2" dia; Dummy antenna.
Ferris	32J		any 40kc/s interval in range 500-1600kc/s is available	10kc/s (estimate)	1μv	QP1 QP2 QP3	multi-vibrator	1/2 meter rod
Measurements	58AS		15-150mc/s	140kc/s(3)	1μv	A QP1 SBP	random noise source	loop 9" dia., Tuned dipole, loop probe, 3" dia, capacitive probe, RF probe
Polarad	FIM		1-10kmc/s with 4 tuning units as follows FIM-L, 1-2.4kmc/s FIM-S, 2.14-4.34kmc/s FIM-M, 4.2-7.74kmc/s FIM-X, 7.36-10.0kmc/s	5mc/s(3)	20μv	A SBP QP1	internal sine wave signal generator	Broadband Conical, Horns
Stoddart	NM-40A	AN/URM-41	a. Selective: 30cps-15kc/s	13-90cps(1) variable	1μv	A	400cps tuning fork oscillator	loop: 30" dia; capacitive probe with dipole
			b. Wideband: 30cps-15kc/s ± 0.5db		15μv	A SBP QP1		
Stoddart	NM-10A	AN/URM-6B	14kc/s-250kc/s	100cps-600cps (2)	1μv	A SBP QP1	neon bulb random noise source	rods: 1 meter and 1/2 meter; loops: 30" and 5 3/8" dia; RF Probe.
Stoddart	NM-20B	AN/PRM-1A	150kc/s-25mc/s	2-6kc/s(2)	3μv	A SBP QP1	random noise source	rod: 1/2 meter; loops: 30" dia, and 7" x 8" rect. loop probe; RF Probe
Stoddart	NM-30A	AN/URM-~~17~~ 47	20mc/s-400mc/s	138kc/s-(2) 175kc/s	1μv to 145mc 2μv to 240mc 6μv to 400mc	A SBP QP1	Impulse generator 60pps	tuned dipole, tuned vertical rod, loop probe 3" dia.
Stoddart	NM-52A	AN/URM-17	375mc/s-1000mc/s	510kc/s(3)	1.6μv to 610mc 2.0μv to 1000mc	A SBP QP1	Impulse generator 60pps	tuned dipole, Broadband "Bowtie"
Stoddart	NM-60A	AN/URM-42	1000mc/s-10.7kmc/s	1.5mc/s(3)	15μv	A SBP QP1	Impulse generator 60pps	Broadband conical, Horns

1. *The bandwidth of this instrument is continuously variable over the range shown.*
2. *The bandwidth of this instrument depends upon the frequency to which the device is tuned.*
3. *The bandwidth of this instrument is virtually constant over the tuning range.*
4. *This unit is tuned in 6 bands; within any one band the bandwidth is said to be virtually constant.*
5. *The bandwidth quoted in this column is either the 6db bandwidth or the "effective impulse bandwidth" defined as the peak output voltage at the dector to an impulse divided by the impulse strength. The latter is for most usual circuits nearly equal to the 6db bandwidth.*
6. *The sensitivity limit is not defined rigorously in most manufacturing bulletins. It may be viewed as the rms amplitude of a sine wave input signal required to equal the detector output obtained from the internal receiver noise.*
7. *Dector functions are designated by the following*

   A = Average of envelope

   SBP = Slide Back Peak

   P = Peak

   QP1 = Quasi-Peak, 1msec charge - 600msec discharge

   QP2 = Quasi-Peak, 10msec charge - 600msec discharge

   QP3 = Quasi-Peak, 1msec charge - 160msec discharge

measures the significant characteristics of the interference directly rather than measuring the response of the RFI meter to the interference. The counter analyzer indicates the rate of rise, amplitude, average level and pulse repetition rate of impulse type interference. It is felt that with this information more effective means of reducing the interference can be designed.

The upper frequency limit of the RFI meter is continuing to keep pace with the ever higher frequencies being used for communication. But there is an increasing need for equipment that will continually monitor the communication frequency spectrum and pinpoint sources of RFI.

CHAPTER XII
BIBLIOGRAPHY AND ABSTRACTS

1. G. A. Morgan, Analysis and Calibration of Loop Probes for Use in Measuring Interference Fields, Naval Research Lab., Washington, D. C., June 1949, (ATI 61713 (3-4)).

"An analysis and calibration were made of loop probes for use in measuring electromagnetic interference fields. The probe consisted essentially of a small shielded loop antenna used for indicating and measuring radio-frequency interference fields from electronic equipment. The input impedance is analogous to an equivalent shorted two-wire balanced transmission line. Loop probes of the approximate dimensions of those analyzed have been shown to be usable for the desired applications at frequencies below 400 Mc only, both because of unsatisfactory response characteristics and because of difficulties of calibration at higher frequencies. The method of calibration uses a second small shielded loop to establish a RF field of known characteristics."

2. M. Engelson, AN/TRM-7 Unique Self Calibrated F.I.M., Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, (AD-253 015).

"The expanding frequency range for which there are military specifications, and the therefore increasing demand for Radio Frequency Interference Suppression, make it desirable to increase measurement speed by decreasing the number of computations and instrument calibration points. The AN/TRM-7 self-calibrating Radio Noise and Field Intensity Meter (0.15-25 Mc) was specifically designed with the above aim in mind. Calibration time is decreased through the use of both an impulse, and a continuously tunable sinewave generator calibrator. Low variation in receiver gain, antenna transfer characteristics and system noise bandwidth reduce computations to a minimum. The discussion includes operational limits, methods of measurements and design philosophy. Included are experimentally determined impulse generator spectra and a discussion of spurious impulse generation as a source of error. The direct reading VTVM capable of pulse measurements below 10 pps and the aural and visual slideback circuitry constitute some of the unique features of this instrument."

3. J. L. Smith, Application of the Low Noise Travelling Wave Tube to Interference Instrumentation, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1959, (AD-235 099).

"The low noise travelling wave tube offers many advantages when used as a system element in microwave interference instrumentation. Following a brief review of these advantages, some of the characteristics of the tube are presented as they apply to interference measuring equipments in the 1 to 11 kmc region. TWT amplifier gain, saturation and gain control characteristics are discussed. In addition, third order intermodulation, input VSWR and desensitization occurring in the tube are considered. In reviewing the characteristics of the TWT, direct emphasis is placed on choosing a desirable tube for instrumentation uses and the manner in which tube characteristics vary with operating parameters."

4. Calibration and Test Procedures for Use with RFI Measuring Set AN/URM-28, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-5366, June 1953.

This report includes a brief description of the complete equipment, theory of operation, calibration procedure, operation and use in measurements.

5. Characteristics and Performance of Apparatus for Measurement of Radio Interference, British Standard, No. 727, pg. 21, 1954.

6. H. Harbottle, The Circuit Noise-Meter (Psophometer) And Its Applications, INSTITUTE OF ELECTRICAL ENGINEERS JOURNAL, Vol. 83, pp. 261-274, Aug. 1938.

"The circuit noise-meter (or psophometer) is an instrument which has been designed for measuring the disturbing effect of power induction on telephone conversation. Measurements have indicated that some form of frequency weighting in the instrument is desirable. The proposed C.C.I.F. specification for the instrument is quoted and discussed. Some useful applications of the psophometer are given. The limitations of present models as applied to other types of noise are reviewed."

7. D. Thom, D. Newby, E. Loveless, C.I.S.P.R. Type Interference Measuring Set Developed in the Central Electricity Laboratory, Brussels, Post Office Radio Report No. 791, England, 1942.

8. Construction and Use of Noise Meter and Harmonic Analyzer, British Electrical and Allied Industries Research Association, Rpt. M/T 38, 1935.

9. R. C. Schwantes, The Counter-Type Interference Analyzer, Lightning and Transient Research Institute, Dec. 1951, (TIP G U23999).

"An interference analyzer designed to indicate the fundamental noise producing properties of radio noise is described. The instrument indicates the average number of times per second that the applied noise waveform exceeds a given rate of rise and a given amplitude, the average level of the noise voltage, and the rate of occurrence of noise pulses that coincidentally exceed the given rate of rise and amplitude during a period when the average level is above any given level. Circuit diagrams and descriptions are given together with results obtained by the instrument with a typical noise source applied."

10. M. Newman, J. Stahman, Counter-Type Interference Analyzer -- Appendix II -- Lightning and Transient Research Institute Rpt. No. 267, May 1953, (AD-56 990).

"Counting techniques have been developed as a method for measurement of impulsive radio interference based on indicating rates of occurrence of the significant noise-producing properties of interference. The counting approach described is a relatively simple method of obtaining much of the information concerning properties of the interference such as could be derived oscillographically, but in a form that can be more directly applied. The counter approach has advantages over conventional noise meters, which essentially indicate only their own particular frequency response to a given interference rather than the character of interference. The counter-analyzer model counts pulse amplitudes and rates of rise above pre-set levels and the coincidence of these factors."

11. Current Probe, Stoddart Aircraft Radio Co., Inc., Final Development Report, 3 April to 29 October 1954.

"This report covers the development and testing of a radio frequency current probe (designated as Radio Interference Current Probe) for making measurements of interference (radio noise) currents flowing in the conductors associated with an interference source. The current probe may be used in conjunction

with a suitable Radio Interference Field Intensity meter for measurements in the frequency range of 0.15 to 25 megacycles per second, and is particularly adaptable for measurement of interference currents in aircraft propellor control circuits."

12. H. Ulfers, The Current Probe, A New Device In the Field of RFI Measurement, Army Signal Research and Development Lab., Fort Monmouth, N. J., Jan. 1961, (AD-249 904).

13. A. Corwin, Design and Construction of a RFI Measuring Set AN/URM-7 and Appendix A, Instruction Manual (Final Report), Empire Devices, Inc., Dec. 1958, (AD-55 274).

"This report covers the development of a compact, portable noise and field strength meter for measurement of electrical field strength as well as for evaluation and suppression of noise originating in electrical and electronic equipment. Part of the development consisted in electrical and mechanical improvements in the government furnished model. In addition, several new components were designed. These included a tuning head covering the range of 400-1000 Mc, dipole antenna and baluns. Each of the component parts is considered in detail. Final test results are presented. Conclusions are drawn and recommendations made for future development."

14. A. Corwin, Design and Construction of RFI Measuring Set AN/URM-85, Empire Devices, Inc., Dec. 1953, (AD-148 302).

15. J. Colebrook, A. Gordon-Smith, The Design and Construction of a Short-Wave Field Strength Measuring Set, INSTITUTE OF ELECTRICAL ENGINEERS JOURNAL, Vol. 84, pg. 388, 1939.

"The paper contains a discussion of the principal features of the design of apparatus for the measurement of field strength at very short wavelengths by means of a loop aerial. The apparatus consists of a high-gain intermediate frequency amplifier (about 1 Mc/sec) associated with a signal frequency and frequency-charge unit of constant conversion efficiency. The e.m.f. of thermal agitation in the input tuned circuit of the IF amplifier is used as a standard signal for setting the amplifier to a known gain. The combination of IF amplifier and signal-frequency unit is calibrated over its signal-frequency range by means of a radiator which gives a horizontally-polarized radiation of calculable intensity. The set can be used for the measurement

of field strengths to the order of microvolts/meter at frequencies of 27-43 Mc with the frequency-charge and aerial units described."

16. A. Borck, M. Rodriguez, Design and Development of a Noise and Field Instrument for 1000 to 12000 Mc/s Frequency Range, INSTITUTE OF RADIO ENGINEERS NATIONAL CONVENTION RECORD VII, Vol.9, pg. 125, 1959.

17. H. Zucker and others, Design and Development of a Standard White Noise Generator and Noise Indicating Instrument, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1958, (AD- 234 212).

"The design and development of a standard white noise generator in the frequency range from 0 to 1000 Mc is presented. The basis of the generator is Nyquist's Law which relates the noise output of a resistor to its temperature. The noise generator consists of a low reflection termination heated in a coaxial furnace. The basis of the design of the low reflection termination is presented together with experimental impedance measurements. The operating temperature of the generator is currently 1300° C. The techniques used in the development of a resistive material to withstand high temperatures are presented together with the temperature characteristics of the termination. The thermal emission effects which occur at the operating temperature of the generator are analyzed. Possible causes for deviation of the generator from a time standard are considered. The design of an instrument to measure the linearity of the generator noise power output as a function of its temperature is presented."

18. A. Macpherson, P. Ridout, R. Searle, The Design of a RF Spectrum Analyzer, Post Office Engineering Dept., England, April 1951, (TIP G R 5663).

"An experimental narrow-band spectrum analyzer, arranged to measure the bandwidth occupied by radio frequency emissions operating in the band 3 to 6 Mc/s is described. Some of the problems connected with the design are discussed, particular mention being made of the effects of "ringing" in the IF filter and the choice of the filter bandwidth. Some photographs are included showing typical spectra obtained with the equipment."

19. F. Colebrook, A. Gordon-Smith, The Design of Ultra-Short-Wave Field Strength Measuring Equipment, INSTITUTE OF ELECTRICAL ENGINEERS JOURNAL, Vol. 90, Part III, pg. 28, 1943.

20. A. Maxwell, B. Bell, The Development and Operation of A Dynamic Spectrum Analyzer, Harvard College Observatory, Cambridge, Mass., Final Report, 1 Apr. 1955 to 30 Mar. 1961, Contract AF 19(604)1394, (AD-260 742).

"A survey is presented of the research work directed towards the study of radio burst emissions from the sun with a dynamic spectrum analyzer consisting of a series of sweep-frequency receivers. Research is reported in six sections: (1) a discussion of the scientific purposes of the program, (2) a brief description of the radio equipment at Fort Davis, together with its manner of operation, (3) a survey of results obtained from analysis of spectral observations of solar radio bursts; statistics of the various types of bursts, their association with flares and prominences, and their relation to emission of high energy particles from the sun, (4) a summary of regularly published patrol data, (5) future programs, and (6) miscellaneous projects in Cambridge."

21. F. J. Trebby, Development of a Square Law Radio Noise Meter, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, POWER APPARATUS AND SYSTEMS, Vol. 78, Part A and B, pp. 522-527, Aug. 1959; pp. 1186-1189 Dec. 1959.

"It has been shown in studies of radio noise generation and propagation on transmission lines that the mean square value of noise voltage is that which can be used most advantageously in calculations and measurements. The circuit design of the square-law radio noise meter is that of a superhetrodyne receiver incorporating a single stage of RF amplification, a converter stage, three intermediate-frequency amplifier stages, and a square-law detector stage. The detector operates as a plate circuit type of detector in conjunction with a d-c milliammeter which measures the average plate current of the detector tubes."

22. Jacob Rosenbaum, Development of Radio Interference Measuring Set AN/PRM-14 ( ), Elk Electronic Labs., Inc., Oct. 1958, (AD-211 487).

"This report discusses the problems encountered and

the solutions achieved in the development of an ultra-compact, lightweight and portable RF interference measuring set. Since ease of maintenance will determine the operational life of equipments, unit sub-assemblies were employed permitting plug-in replacements of parts and/or units reaching the end of their useful life. Since some of the data found in the Instruction Book is helpful in achieving a better overall understanding of this equipment, the complete Instruction Book for the AN/PRM-14 is included."

23. Development of RFI Measuring Set AN/URM-37, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-5160, Jan. 1953.

"The Model 1A radio-interference tester was a special type of radio receiver designed for reception of radio-interference signals, and was capable of responding simultaneously to a range of radio frequencies covering several hundred megacycles. The present project was established to determine the feasibility of adding certain desired features to increase the utility of the instrument. The project objectives were achieved by a design which retained the basic principles of this Model 1A but which more fully exploited the capabilities of this type of instrument. With respect to portability, battery life, stability, uniformity of equipments, simplicity of construction, maintenance, and operation, the new instrument was found to be inherently superior to tuned receivers."

24. D. C. Rohlfs, W. W. Balwarz, F. E. Boyd, Electromagnetic Probes for Near Zone Measurements, Naval Research Lab., Washington, D. C., NRL 5378, Oct. 1957, (PB-142 451).

25. W. Stinger, Evaluation of Empire Devices NF-105 Noise and Field Intensity Meter, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-61113, 18 Dec. 1961.

"A noise and field intensity meter was evaluated to determine its suitability for making radio interference measurements in accordance with military requirements. The results indicated that the meter is acceptable for measuring the parameters of interference signals required by the specifications at frequencies between 0.15 and 1000 mc. The performance of the meter compares favorably with the

performance of the AN/PRM-1, TS-587/U, and AN/URM-17 interference measurement devices."

26. W. Jarva, Evaluation of Radio Interference Pick-Up Devices and Explanation of the Methods and Limits of Specification No. MIL-I-6181B, Naval Air Development Center, Johnsville, Pa., Rpt. No. NADC-EL-5515, Aug. 1955, (PB-129 688).

27. C. Burrill, An Evaluation of Radio Noise Meter Performance in Terms of Listening Experience, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 30, pg. 473, Oct. 1942.

"(Tests were made)...for the purpose of indicating how closely instruments made in accordance with the latest radio-noise meter specification of the Joint Coordination Committee meet the objective of giving readings proportional to annoyance for all types of radio noise. Thirty people participated in the tests which involved three types of radio noise and three different radio-noise meters. Standard statistical methods are used in analyzing the results, and these methods are explained in simple fashion for the benefit of radio engineers who are unfamiliar with statistical science. The general conclusion is that the new radio-noise-meter performance is very satisfactory."

28. H. Mertel, J. Fischer, Existing Current Probes and Development of New Probes to 1 KMC, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 205).

"This paper presents the development and the evaluation of current probes to measure conducted interference in the frequency range of 30 cps to 1000 Mc. Four commercially available current probes for the 30 cps to 1000 Mc were evaluated. Two current probes were developed for the 20 Mc to 1000 Mc frequency region. One current probe was developed to measure interference currents in large diameter cables. The sensitivity of these current probes is sufficient to detect interference currents below most existing specification limits. Several methods are given to calibrate the current probes. In the 300 Mc to 1000 Mc frequency range, the current probes were calibrated by an antenna method."

29. A. Mamford, P. Barker, A Field Strength Measuring Set Using Thermal Agitation Noise as the Calibrating Source, POST OFFICE ELECTRICAL ENGINEER'S JOURNAL, England, Vol. 28, pg. 40, 1935.

30. A Harmonic Analyser for General Purpose and Noise Analysis, British Electrical and Allied Industries Research Association, Rpt. M/T 54, 1937.

31. An Improved Harmonic Analyser and Noise Meter, British Electrical and Allied Industries Research Association, Rpt. M/T 108, 1950.

32. J. Vogelman, An Impulse Generator for Receiver Performance Measurement, INSTITUTE OF RADIO ENGINEERS NATIONAL CONVENTION RECORD, Pt. 5, pp. 3-11, 1954.

"An impulse generator has been developed consisting of a uniform transmission line which is periodically charging and discharging into a specified output impedance. The ratio of the transmission line impedance and the load impedance being selected so as to produce the flattest possible frequency spectrum over a frequency band from the very low frequency to in excess of 15,000 Mc. The spectral analysis of the current in the output wave form of the idealized impulse generator shows a flat response to about 85 per cent of resonant frequency over the transmission line. The results obtained by impulse measurement of receiver performance are compared to other means now being utilized."

33. Instrument Aids Radio Interference Evaluation; ADVisor System, ELECTRICAL WORLD, Vol. 155, pg. 62, March 13, 1961.

Describes an automatic digital data collecting device. The data stored on tape will be used to draw correlations between weather conditions and RF interference emitted by power lines.

34. F. Knapp, W. Lambdin, An Instrument for Measurement of High RF Power Density, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, pg. 406, Oct. 1960, (AD-253 015).

"The first portion of this paper considers the need for an instrument to permit rapid measurement of high RF power densities and immediate awareness of areas presenting RF hazards to personnel. The present state of knowledge as to the degree of hazard presented by various RF power densities is reviewed briefly. Functional requirements of an instrument to provide accurate and rapid measurements are next considered with attention devoted to the broad frequency range and wide dynamic range required, the

desirability for a direct reading feature, and the need for extreme portability. The actual instrument resulting from consideration of these various factors is then described in some detail with special attention to the battery power source and to the antenna probes which are designed for constant gain; to permit direct reading of power density in milliwatts/cm^2 at any frequency from 200 to 10,000 MC."

35. J. Chappell, Instrumentation for Interference and Field Strength Measurement, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, pg. 55, Dec. 1954, (AD-76 686).

"Problems of radio interference and field strength measurement are discussed and measurement equipment developed to cope with these problems is described. The problems discussed relate primarily to imposed conditions under which interference and field strength measurements must be made, and the nature of interference together with the particular interference characteristics which are to be measured. The measurement equipment is described from the standpoint of the measurement system employed and the instrument characteristics that are considered unique."

36. F. Haber, R. M. Showers, Instrumentation for Radio Interference Measurements, ELECTRONIC INDUSTRIES, Vol. 20, pp. 110-116, March 1961.

"The background and present status of the field survey type of radio noise measuring instrument is described. These devices are designed for the measurement of all kinds of noise either in terms of some comparison standards, for example, an impulse source, or in terms of a standard circuit, such as the quasi-peak circuit. In some instruments, more than one measure of the noise is provided and these often provide a basis for distinguishing between classes of noise. To a large extent, measurements using such instruments are made to compare the strengths of similar sources of radio noise, and to a lesser extent, to determine the relative interference effect of different radio noises. In many cases, however, such instruments do not provide adequate data for establishing the loss of information in a communication system."

37. T.W. Tunney, Jr., An Integrated Airborne System of Field Intensity Measuring Equipment, Melpar, Inc., Falls Church, Va., Final Engineering Rpt. for Phase 2, Nov. 1958 to

Oct. 1959, Rpt. No. AFMTC TR-59-23, Contract AF 08(606) 1789, (AD-227 992).

"Research was continued in an effort to design and develop an integrated airborne field intensity measuring equipment. The integration of components and the calibration of the field intensity antennas are described. Field flight tests completed at Patrick Air Force Base, Florida, are described and test results are presented."

38. Interference Analyzer, Final Report, Lightning and Transients Research Institute, Aug. 1951.

"The analyzer comprises a dual-beam oscillograph, 11 noise-meter-type receivers, and commutation and metering circuits. The 25 KV dual-beam CRT with sweep and two independent video channels permit observing two phenomena at once or one phenomenon at two different sweep speeds. The video amplifier for Channel A has a wide bandwidth which is substantially flat from 0.1 to 250 Mc. The receivers and commutation circuits when used with Channel B permit observation of the effect of interference on receivers having a 0.1 to 700 Mc frequency range. Two conduction and three electromagnetic loop probes are used to pick up the interference signals and feed them to the input circuits. The input circuits consist primarily of the various lumped constant coupling networks, the lumped constant transmission line, the isolating stages, and the coupling stage."

39. Interference Analyzer--Handbook of Instruction, Lightning and Transients Research Institute, Aug. 1951, (ATI-139 888 (3-4)).

"A handbook of instructions for use with the interference analyzer is presented. The analyzer is to be used in the study of the nature of electrical noise and the effect of electrical noise on electronic equipment. The instrument displays oscillographically interference pulses after amplification by a wide bank transmission line amplifier. By this means, atmosphere interference and interference generated by a relay, motor, or other electrical apparatus may be examined closely. This instrument is also designed to present panoramically on a cathode-ray tube the output of series of receiver type noise-meters shock excited by the interference pulse and tuned throughout their frequency ranges. Thus the effects of the interference on electronic equipment over a wide frequency range may be studied."

40. R. E. Bloom, R. J. Fleisher, H. A. Favors, Interference and RFI Meter, INSTRUMENTS AND CONTROL SYSTEMS, Vol. 34, pp. 1443-1449, Aug. 1961.

"Accurate RFI measurements demand careful consideration of the type of signal measured, the RFI meter used, and the accuracy to which the meter is calibrated. This article discusses interference sources, the RFI meter, and calibration set-ups."

41. W. Stokes, H. Hicks, An Investigation of Electromagnetic Coupling Devices for the Measurement of Noise Fields, Rensselaer Polytechnic Institute, Quarterly Rpt. #1, (Sept.1 to Nov. 30, 1950), (TIP G U18177).

"A study was undertaken to improve the methods of measuring broadband interference from ignition systems, rotating machinery, electronic equipment, and similar devices over the 0.15 to 400 Mc range. Emphasis was directed to the portion of the measuring system which couples the interfering field to the interference meter. Interference measurement equipment in current use is discussed. The methods which appear promising for improving the coupling between the interfering field and the measuring equipment are the use of a shielded room and small, high-gain probes. The theoretical development of the shielded room is presented, and it indicates that by measuring the current at various points on the wall of the room one can determine the strength of the radiator at the center of the room. The fundamental properties of small electric and magnetic probes are discussed and S/N ratio is investigated theoretically."

42. W. Stokes, H. Hicks, and others, An Investigation of Electromagnetic Coupling Devices for the Measurement of Noise Fields, Rensselaer Polytechnic Institute, Quarterly Rpt. #2, (1 Dec. 1950 to 28 Feb. 1951), (TIP G U18178).

"Work on the shielded room revealed the presence of modes due to the feed cable. These were not predicted theoretically, and further study was indicated to determine their effects. The corner-loop method and the effect of a radiating loop in a box are discussed. Theoretical and experimental observations were made on the high gain electric probe. An arbitrary figure of merit was established which properly weights the various factors involved in the utility of a pick-up device. Work on the amplifier and high-gain arrays substantiated the validity of this method of attack and showed that signals of the order of

"0.2 microvolts will give a signal to noise ratio of unity at 1 mpcs, when the amplifier is driving a receiver with a sensitivity of about 2 microvolts at the same frequency."

43. Measurement of Radio Interference In Frequency Range 0.15 to 30 Mc--Portable Measuring Set, British Electrical and Allied Industries Research Association, Rpt. M/T 116, 1953.

44. A. MacPherson, Measuring Equipment, POST OFFICE ELECTRICAL ENGINEERS JOURNAL, England, pp. 115-119, July, 1958.

"Basic characteristics of radio interference and principles of measurement are discussed. General design and development details of equipment for use by the Post Office in interference measurements are given."

45. H. Leingangg, Measuring Equipment for Radio Interference in the U.S.W. Range, Rhode und Schwarz Mitt, No. 3, pp. 120-125, May 1953.

"Describes and illustrates equipment for measurement of radio interference in the range 30-180 Mc and 85-330 Mc, and its calibration. Compares standard British and German measurement equipment."

46. J. McPetrie, B. Pressey, A Method Using Horizontally Polarized Waves for the Calibration of Short-Wave Field Strength Measuring Sets by Radiation, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 83, pg. 210, 1938.

"The paper describes a method for the calibration of short-wave field-strength measuring sets by radiation using loop transmitter in the horizontal plane. It is shown experimentally that in the case of vertically polarized waves the simple ray theory does not apply unless the transmitter and receiver are both elevated to considerable heights above the ground. With horizontally polarized radiation, however, the simple ray theory holds on short waves for practically all heights of transmitter and receiver. This distinction between the propagation characteristics of the two types of radiation suggests the use of horizontally polarized waves for field strength calibrations on short waves."

47. B. Rosen, Microwave Field Intensity Meter, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1958, (AD-234 212).

"This paper discusses some of the problems in the development of a high frequency microwave receiver. The basic system will be described with a presentation of the system requirements that were considered during the development."

48. R. Schwartz, C. Polk, Microwave Noise and Field Intensity Meter Development, Moore School of Electrical Engineering, Final Report, Apr. 1953, (AD-23 019).

"With the objective of investigating the feasibility of constructing a microwave noise and field intensity meter, detailed component studies were made. These are summarized in this report. Conclusions regarding the feasibility are presented. A discussion of the work accomplished on low gain antennas is given, and the items to be specified for the design are set forth. Investigation of microwave attenuators is summarized briefly, and alternatives for future study are outlined. The work on preselectors is mentioned, and an alternative to coaxial type units proposed. Rather extensive tests are reported on a local oscillator in which a triode oscillator drives a crystal harmonic generator. A CW microwave calibration source is described. A detailed description of intermediate and low frequency circuit designs is given."

49. W. Gerber, J. Meyer De Stadelhofen, New Instruments for the Measurement and Suppression of Interference, Translated by F. A. Raven, TECHNISCHE MITTEILUNGEN of Swiss Telegraph and Telephone Authority, July 1951, (PB-106 226).

50. A. Koelle, G. Johnson, Jr., A New Peak VTVM for Interference Measuring Sets, Proceedings of the 2nd Conference on Radio Interference Reduction, Armour Research Foundation, March 1956.

51. S. Manfanovsky, W. Lambdin, A Noise and Field Intensity Meter for the Frequency Range from 1 to 10 KMc, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, (AD-253 015).

"The first portion of the paper treats the system considerations appropriate to the development of a noise and field intensity meter for this wide frequency range and includes a discussion of the resulting system parameters. After a block diagram of the entire device is presented, emphasis is shifted to a more detailed consideration of the unique solutions incorporated to special problems

which the stringent systems requirements caused in the klystron and metering circuits. Other aspects treated include the compact, mechanical configuration, incorporating the plug-in head concept, and the utilization of a single broad-band high gain antenna over the entire operating range of the device. The concluding section of the paper considers field applications, with special attention to the flexibility and ease of calibrating afforded by the inclusion of a broad-band impulse generator."

52. Noise Measuring Set AN/URM-8, General Lab. Assoc., (Int. Rpt. June 3 to July 3, 1950), (TIP G R3885).

"Mechanical and electrical requirements are outlined for the LF tuner which can follow a prescribed tuning curve. A pulse generator was developed capable of producing variable delay time from 3 to 10,000 Mc, but requires many tubes. The unit can also be used as a sinewave generator by simple switching."

53. Noise Measuring Set AN/URM-8, General Lab. Assoc., (Int. Rpt. July 30 to Oct. 7, 1950), (TIP G R3926).

"VHF circuits using butterfly tuners were established. In the UHF tuned circuits, the RF amplifier consists of push-pull type 6F4 with grounded grid and the mixer circuit comprises two balanced crystals in conjunction with a butterfly circuit. A temperature vs. frequency test on the LF tuner from 100 to 1000 Kc indicated that the Curie point of about 130° C for the high permeability core produced less than 1% change in frequency."

54. A. Eckersley, Noise Meter Calibrator Studies, Moore School of Electrical Engineering, Dec. 1951, (TIP V U 21740, V U22832, V U23475, V U24708).

55. F. Conrad, On the Measurement of High Frequency Interference, ELEKTRISCHE NACHRICHTENTECHNIK, Vol. 18, No. 6, pp. 126-133, June 1941.

"States that the frequency spectrum of HF interference must be determined before adequate measurement equipment can be designed. These spectra must be known both at the source and after radiation or conduction from the source. That ultra short wave emission or emissions in the decimetric wave range from improperly shielded apparatus will interfere with interference measurements. Discusses the characteristics which measuring devices must have in order to properly measure HF interference levels. The device

can be identical to a standard receiver for all stages up to the rectifier. However, the rectifier must not be overcontrolled. The use of superhet receivers for noise intensity measurements is discussed. In most cases, consistent results from different equipments are almost impossible to obtain unless the equipments are electrically and electroacoustically identical.

56. R. Powers, A 1 to 10 KMc Panoramic Receiving System for RFI Monitoring, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 205).

"A voltage-swept Panoramic Superheterodyne Receiving System covering the range from 1 KMc to 10 KMc has been developed for the rapid intercept and monitoring of radio frequency interference. Known as the AN/GRR-9, the equipment is contained in a standard 6-foot relay rack except for the indicators, which are in a separate bench-mounted case, and the antennas, which may be mounted on a tripod or a rotatable mast. The entire frequency range of 1 to 10 KMc is covered continuously and simultaneously in four bands (1 to 2 KMc, 2 to 4 KMc, 4 to 7.2 KMc and 7.2 to 10.3 KMc) at sweep rates of either 15 cps or 60 cps with receiver sensitivities as high as -95 dbm. Each band is provided with a CRT indicator which displays signal amplitude vs. frequency."

57. D. D. Hughes, Performance of the AN/URM-37 for Radio Interference Measurements, Naval Civil Engineering Lab., Port Hueneme, Calif., 20 May 1957, Proj. NY 411 002-3, (AD-221 777).

58. Phase I Report--Design Evaluation of Spectrum Analyzer TS-694 (XN-   )/UP Mfgd. by Polytechnic Research and Development Co., Brooklyn, Naval Air Development Center, Johnsville, Pa., Rpt. NADC-EL-L5324, March 1953, (AD-10 414).

59. H. Beer, R. Swindlehurst, W. Bray, Portable Radio Interference Measuring Set, Post Office Radio Report No. 330, 1937.

60. W. Pakala, R. Showers, Principles and Application of Radio Interference Measurements, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS, Vol. I-7, pp. 297-303, Dec. 1958.

"The purpose of this paper is to review the present status of radio interference instrumentation, the problems associated with its use and standardization,

and to describe the problem areas of future development."

61. C. M. Burrill, Progress in the Development of Instruments for Measuring Radio Noise, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 29, pp. 433-442, Aug. 1941.

"Following a brief discussion of the nature of radio noise, the basic problems of radio-noise measurement are outlined. The paper concludes with a chronological account of the different instruments which have been used to measure radio noise, with descriptions of the fundamental characteristics of each. Particular attention is given to a quasi-peak type of radio noise meter with logarithmic scale."

62. Proposed Military Specifications for Field Meter Strength Radio (TS 509), Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Rpt. NADC-EL-5496, Aug. 1954.

The meter is described as follows: "The equipment covered by this specification shall be a Meter, Field Strength, (Radio), TS-509/UR, capable of providing a direct visual means of determining the relative field strength, power, and frequency of radio-frequency signals falling within the frequency range from 100 to 400 megacycles per second. The meter shall be suitable for use in maintaining and testing airborne and other electronic equipment."

63. B. G. Pressey, G. E. Ashwell, A Pulse Field Strength Measuring Set for Very High Frequencies, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, Part III A, Vol. 93, pg. 1359, 1946.

"The paper describes a portable equipment for the measurement of the field strength of pulse and continuous-wave signals in the frequency bands 20-30 and 40-650 Mc/s. The equipment consists essentially of a receiver, in which are incorporated calibrated signal-frequency and intermediate frequency attenuators and an output meter, and a cathode-ray output-indicator unit. The field strength is measured by adjustment of the attenuators for a standard output, which for pulse signals is read on the cathode-ray tube and for continuous-wave signals on the meter. A half-wave dipole aerial is used, and the initial calibration of the standard output in terms of the field strength at the

aerial is carried out by a radiation method. The noise voltage of the first circuit of the intermediate-frequency amplifier is used as the reference voltage for setting up the gain of the amplifier and an internal oscillation supplies the reference voltage for setting the gain of the indicator unit."

64. E. Malowicki, QRC T-21 Interference Locator, Rome Air Development Center, TR-56-2, Feb. 1956, (AD-86 527).

"QRC T-21 is a short-range, ground-transportable, passive Electronic Countermeasure (ECM) device for seeking out interference radio frequency signals in the L and S bands. It is capable of direction-finding action on signals with no modulation. An AN/USM-32 oscilloscope provides visual indication of the presence of amplitude or pulse-modulated signals above a minus 80 dbm level. Headphones provide audible indication of amplitude or pulse modulated signals above a minus 80 dbm level. A continuous wave meter provides visual indication of the presence and relative strength of CW signals above a minus 70 dbm level. For D/F action the T-21 utilizes a directional horn mounted on a collapsible tripod. The horn is normally in the vertically polarized position."

65. RFI Measuring Set (1000-10,000 Mcs) AN/TRM-(XA1), Polarad Electronics Corp., 10 Oct. to 31 Dec. 1954, (AD-57 131); 1 April to 30 June 1955, (AD-77 371).

66. F. Brown, RFI Studies, Measurements, and Evaluation of Electro-Medical and Development of Improved Magnetic Field Pick-up Device for the AN/PRM-1 Field Intensity Meter, Electro-Search, Phila., Pa., Sept. 1954, (AD-78 646).

"A breadboard model of an improved magnetic field pick-up device for the AN/PRM-1 Radio Interference Field Intensity Meter is described. Conclusions are drawn from the work and recommendations are presented."

67. A. Corwin, RF Interference Test Set AN/PRM-14, Final Report, Empire Devices, Sept. 1950, (AD-26 711).

"This report covers the development of a compact, portable noise and field strength meter for measurement of electrical field strength, as well as for evaluation and suppression of noise originating in electrical and electronic equipment. Each of the component parts is considered in detail. Final

test results are presented. Conclusions are drawn and recommendations made for future development."

68. Radio Interference Measuring Apparatus for the Frequencies 25 Mc-300 Mc, CISPR Regulation, CISPR (Central Office) 303.

69. F. McMillan, H. Barnett, A Radio Interference Measuring Instrument, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS, Vol. 54, pp. 857-862, Aug. 1935.

"The instrument described in this paper provides a means for measuring with acceptable accuracy both crest and effective values of interference field strength, the ratio of which agrees with observed discrepancies between effective and apparent values."

70. Radio Interference Measuring Set AN/TRM-7(XA-1), Polarad Electronics Corp., Long Island City, N. Y., Final Engineering Rpt. No. 4110/FR, Contract AF 33(600)33023, Aug. 24, 1960, (AD-245 848).

"Details are given of the methods and results of the design and development of Radio Interference Measuring Set AN/TRM-7(XA-1). Theoretical and experimental results are presented for the circuits developed and tested. Final performance data and recommendations for improvements are included. In particular the report discusses the system design considerations which included the choice of a turret tuner and a synchronously tuned sine wave generator calibrator. Recommendations on methods of reducing the size and weight of the equipment are also included."

71. Radio Interference Measuring Set AN/URM-3, U. S. Army Signal Corps, TM 11-5084, 29 Aug. 1956.

72. Radio Test Set AN/URM-41(VLF Interference and Field Intensity Measuring Equipment), Televiso, Corp., March 1952, (TIP G U23213).

"Progress is reported on the development of equipment for measuring VLF radio interference and field intensities. The instrument is required to (1) measure field intensities of sinusoidal magnetic and electric fields over a frequency range of 30 to 15,000 cps; (2) perform harmonic analysis of periodic and random disturbances by utilizing direct coupling, or electric or magnetic pick-up in conjunction with a proper calibration chart; (3) operate as a selective 2-terminal vacuum tube voltmeter over its

complete frequency range; and (4) operate as an aperiodic 2-terminal VTVM (untuned) for observing pulse and other disturbances and coupled to the metering section and phone and CRT terminals."

73. Rebuilding and Reconditioning of One (1) Each R-F Impulse Spectrum Analyzer, Final Report, Lynmor Engineers, Phila., Pa., Jan. 1960, (AD-221 410).

74. M. Levine, Receivers for Interference Measurements in the 20 to 4000 Megacycle Range, Proceedings of the 4th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1958, (AD-234 212).

"The design of wide-tuning-range receivers for the measurement of radio interference presents several unique problems. The special requirements of such receivers are discussed and a design philosophy which minimizes these problems is presented. A series of receivers which cover the frequency range from 20 to 4000 Mc is described for illustration. These receivers are intended to be precision instruments with accurately predictable and reproducible characteristics. Special emphasis has been placed on accuracy of impulse measurement and the suppression of undesired responses and intermodulation products."

75. Receiver for the Investigation of S. W. Interference Radiated by Ignition Systems, ENGINEERING, Vol. 161, pp. 42-43, Jan. 10, 1936.

76. T. Chew, Relative Field Strength Meter for Locating Interference and to Discover the Best UHF Antenna Location, RADIO NEWS, Vol. 25, pp. 19-20, May 1941.

77. R. Showers, A. Ackersley, Research Investigation of Interference Measuring Instruments, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"Certain general requirements of a radio interference measuring instrument are stated. Radio noise meters have been developed with specified characteristics to assist in the analysis and reduction of man-made interference. Some of the technical problems and design features of equipment designed to meet current requirements are discussed."

78. D. B. Geselowitz, Response of Ideal Radio Noise Meter to Continuous Sine Wave, Recurrent Impulses and Random

Noise, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. 3, No. 1, May 1961.

79. Service Test of Radio Interference Measuring Set XAN/PRM-14, Army Airborne and Electronics Board, Fort Bragg, N. C., Proj. No. CE 960, 19 Aug. 1960, (AD-242 770).

"Tests were conducted to determine the suitability of Radio Interference Measuring Set XAN/PRM-14 for Army use. The XAN/PRM-14 is a portable test instrument designed for interference location and measurement within the frequency range of 150 kilocycles to 80 megacycles. Measurement of noise intensity is made possible by means of a built-in calibrated impulse noise source. Measurements may be taken using either visual (meter) or aural means. The XAN/PRM-14 when modified may be suitable for Army use in temperate climates."

80. Specifications for Radio Noise Meter, ASA C 63.2, ASA, 70 East 45th St., New York 17, N. Y.

81. H. Friis, A Static Recorder, BELL SYSTEM TECHNICAL JOURNAL, No. 5, pg. 282, 1926.

Describes an early instrument for recording static. The set made use of a fluximeter with zero restoring torque by means of which the rectified output current arising from static interference is integrated over a period of ten seconds. The following five seconds were required to adjust the gain of the amplifier and record the change in gain from an arbitrary level. A record is shown during which the intensity of static changed by a factor of more than 10,000.

82. R. Schulz, Studies, Investigations and Applied Research Concerning Radio Interference Instrumentation, Development of Pick-Up Devices and Evaluation of Electro-Medical Equipments, Electro-Search, Interim Rpt. #12, May 1 - 31, 1952, Aug. 1951, (TIP G U23204).

"Tests on the filters in the link coupling of the Burdick MF-49 diathermy unit produced unsatisfactory results. Modifications utilizing a field-cancellation approach on the capacitor electrodes of the Liebel-Flasheim Model SW-660 diathermy unit indicated that an attenuation of 10:1 or better can be obtained."

83. R. B. Schulz, Studies, Investigations, and Applied Research Concerning Radio Interference Instrumentation,

Development of Pickup Devices and Evaluation of Electro-Medical Equipments, Electro-Search, 1 Sept. 1952 to 30 Sept. 1952, under Contract NObsr-52386, Oct. 1952, (PB-108 284).

Report describes all work performed under contract. Other reports summarized for electro-medical equipment. Pickup devices and R-I instrumentation reported in detail.

84. Studies of Modularization Techniques as Applied to RFI Measuring Set AN/URM-47, Stoddart Aircraft Radio Co., Nov. 1957, (AD-84 218).

"This report covers developmental work accomplished during the period 21 March 1955 through 20 June 1955 on Navy Contract NObsr-64592. Data on the various phases of work done on the second modularized AN/URM-47 is presented. Procedures followed and problems encountered are explained in detail. Preliminary testing and alignment of the first completed modularized AN/URM-47 is described."

85. J. L. Smith, T. Thomas, A. Mallett, Study Program for Radio Interference Measuring Set AN/URM-100, Collins Radio Corp., Oct. 1959, (AD-226 976).

86. F. A. Giordano, Technical Evaluation of AN/URM-131(XN-1) Radio Interference Field Intensity Measuring Equipment, Final Report, Material Lab., New York Naval Shipyard, Brooklyn, Lab. Proj. No. 6296, 24 July 1961, (AD-267 851L).

"The AN/URM-131(XN-1) radio interference field intensity measuring equipment, covering the frequency range from 150 kc to 30 mc was technically evaluated. The results of the tests performed are presented, together with recommendations. A comparison of the sensitivity of AN/URM-131(XN-1) with its predecessor, the AN/PRM-1, was made. The AN/URM-131 radio interference field intensity measuring equipment is a sensitive radio receiver which operated in the range of 150 kc to 32 mc in 8 bands. As an RF voltmeter this equipment is capable of measuring signals as low as 0.1 microvolt and as high as 1 volt.

87. C. M. Wooten, Technical Evaluation of Field Intensity Meter NM-52A, Final Rpt., Naval Air Test Center, Patuxent River, Md., Problem No. 60-16 ID (695B), 3 March 1961, (AD-264 024L).

"The radio interference-field intensity meter NM-52A was technically evaluated and compared to its prototype, radio test set AN/URM-17. The NM-52A RI-FI Meter is a sensitive radio receiver, operating as a selective radio frequency voltmeter over the 375 to 1000 mc portion of the radio spectrum. As a selective RF voltmeter, it can measure RF voltages in the range of 1.0 microvolt to 1.0 volt. As a field intensity meter with an antenna supplied, it can measure 10 microvolts per meter to 10 volts per meter (at 375 mc). It was concluded that with suggested modifications, the NM-52A is superior to the AN/URM-17."

88. A Thermistor Bridge Voltmeter for Calibrating Interference Measuring Instruments, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1959, (AD-235 099).

"The paper describes work done to devise a standard procedure and instrumentation for amplitude calibrating radio interference/field intensity meters over a voltage range from 100 μV to 100,000 μV for frequencies from 14 Kc to 1000 Mc. The frequency-sensitive input impedance of these instruments precludes the use of calibrated signal generators since the source amplitude is known only for matched outputs. The result of the project is a thermistor bridge designed and calibrated to read directly rms volts at the instrument terminals from 5000 μV to 100,000 μV. Also described is the coaxial switching and attenuator system used in conjunction with the bridge to calibrate the ri/fi instruments down to 100 μV. Several interesting features of the bridge are covered in detail including: (1) A unique method of temperature compensation, (2) A pulsing procedure for comparing the r-f voltage with a reference d.c.signal, and (3) A potentiometer measuring circuit that gives rise to a quasi-logarithmically calibrated indicating dial."

89. W. M. Grim, Jr., The Voice Interference Analysis Set, An Instrument for Evaluating the Performance of a Voice Communication Channel, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 205).

"The Voice Interference Analysis Set rapidly and accurately analyzes the performance of a voice communication channel in the presence of interference. The analysis is computed on the basis of a 14-band

Articulation Index Calculation as developed by French and Steinberg. A modulated pilot tone, which replaces the usual speech signal, is transmitted over the link under test. At the receiver, the tone is used to normalize the interference so that noise-to-signal ratio measurements can be made in each of the bands. The individual channel outputs are then properly combined to produce the final output. Analog and coded digital outputs are provided in addition to a front panel indication. In addition to simple cases of white and shaped noise, the system can evaluate, individually and in combination, complicated cases involving reduced transmission path band width, peak clipping at the transmitter, narrow band interference, and interrupted interference."

90. H. Beer, W. Bray, W. Lowry, Wide Range Portable Noise Field and Voltage Measuring Set, Post Office Radio Report No. 330, 1937.

91. R. Hubbard, J. Cateora, An X-Band Field Intensity Recording Receiver with Extremely Narrow Bandwidth, IRE-URSI Joint Meeting, San Diego, Calif., Oct. 1959.

CHAPTER XIII

METHODS OF MEASURING RADIO FREQUENCY INTERFERENCE

The measurement of radio interference can be separated into three distinct areas. Two of these--location and identification--would normally be accomplished at the same time. The interference can be located by use of a receiver with a directional antenna or by systematic isolation of potential sources. Closely related to this is the identification of the interference--categorizing it by sound from the audio output of the detection equipment or by waveform in both the time and frequency domain. The third area is the actual measurement of the interference intensity. Interference may be either or both of two types--radiated and conducted.

As indicated above an unknown source of interference can be located within a general area utilizing the directivity of an antenna array and triangulation. In many cases, such as industrial plants, there may be many potential sources of interference within the triangulated area. To determine the location of interference within a particular piece of equipment such as an ignition system, a probe is used. The probe is usually insulated so that it may be used in close proximity to high voltage components.

In order to further narrow the number of possible sources, identification by sound or waveform may be used. The Signal Corps Guide for Manufacturers, ref. (82), gives the

following table correlating types of audio noise to possible sources.

Type of Noise	Possible Source
Clicking, regular or irregular	Electric calculating machines Code machines Mercury arc rectifiers Relays Switches Teletype machines Thermostatic controls Typewriters, electric
Popping	Ignition systems Magnetos
Buzzing	Buzzers Vibrators
Crackling	Regulators
Whining	Devices using electric motor generators
Loud continuous sputtering	Arc welders High frequency apparatus, diathermy, etc. Arc lamps

Fig. XIII - 1 Types of Audio Noise Correlated with Possible Sources

Interference can also be identified, and hence in many cases located, by its "electronic signature". Myers, in ref. (25), has depicted many of these waveforms. For instance the "electronic signature", or frequency-time-field intensity relationship of the radiation from a mercury arc rectifier can be easily expressed in graphs of frequency versus time, and field intensity versus frequency as shown in the following diagrams.

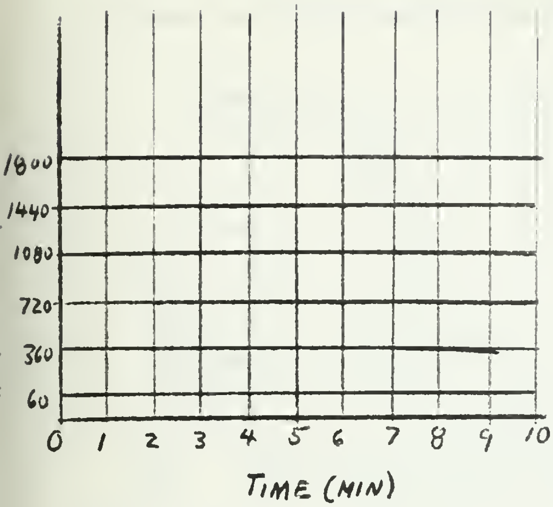

Fig. XIII - 2
Frequency-Time Signature of a Six Phase Mercury Arc Rectifier

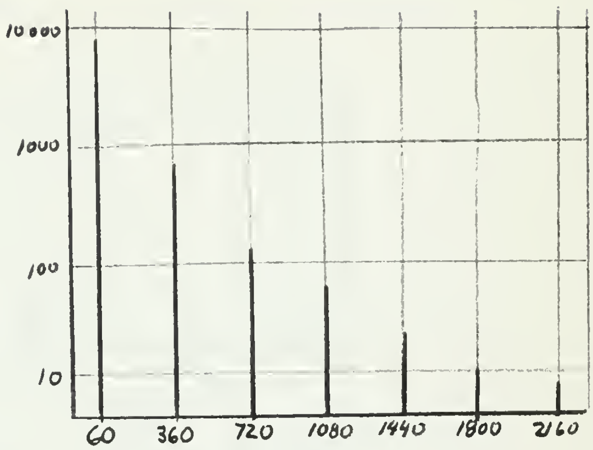

Fig. XIII - 3
Field Intensity-Frequency Signature of a 6 Mercury Arc Rectifier

In automobile ignition systems frequencies above 50 mc are attenuated due to shielding. As shown below there are two peaks--one is at 200-400 kc and is due to the combination of the coil inductance and the distributed capacitance of the leads, the other is at 20 mc, the natural resonant frequency of the ignition system.

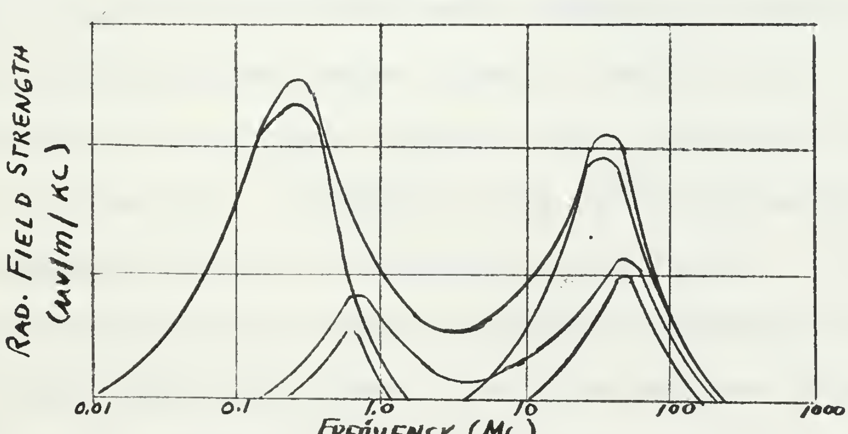

Fig. XIII - 4 Measured Automobile Engine Radiated Electric Field

Figure XIII - 5 illustrates typical interference spectra from fluorescent lamps, indicating the usual interesting increase at the lower frequencies.

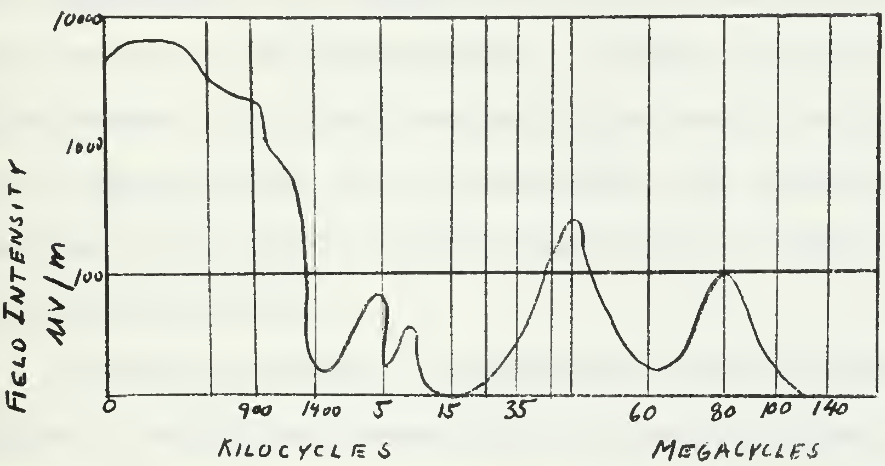

Fig. XIII - 5 40-watt Fluorescent Lamp Radiated Interference

It is apparent that the radiation from automotive ignition systems is distinctly different from that of rectifiers and fluorescent lamps. Therefore different radiating sources can be identified through the use of panoramic receivers and displays.

Interfering signals can be further classified into the impulsive type in which the pulse duration is small compared to the period and the random type, a "white noise", in which the pulses are very close together and individual pulses cannot be singled out. Impulsive type interference has high peak values but very low average or rms values. In the case of random interference there is little difference between the average and peak values. The interference is usually

measured in one of three ways; the average or rms value, the peak value, or the quasi-peak value. The quasi-peak indication on the meter increases with an increase in repetition rate therefore it is considered to be a measure of the "nuisance" value of the interference. Since a majority of impulse interference is of the broadband type and a receiver's output is proportional to its bandwidth, the interference is measured in the peak position and given in volts per meter per unit bandwidth.

Generally speaking, interference can be transmitted either as radiation through the air or by conduction through a cable. Conducted interference is measured at the power terminals of various equipments, from which interference may be transmitted through the power cables to receivers. Conducted measurements are made using the field intensity meter as an RF voltmeter in conjunction with special coupling and impedance matching networks.

When making field strength measurements of radiation the measuring equipment must have calibrated antennas in order to accurately determine the volts per meter factor. In addition the loss in the transmission line between the antenna and the RI meter as well as the effective height of the antenna must be considered if accurate field strength measurements are to be obtained.

A substitution measurement technique, described by Chappell in ref. (28), makes the measurement independent of

both antenna impedance and input circuit impedance. This method provides for the measurement of the unknown interference in terms of the output of a calibrated impulse generator which will give the same peak response to a superhet receiver as the unknown interference. The impulse generator, calibrated in microvolts/unit of bandwidth, is inserted in the antenna circuit of the receiver so that the interference meter measures the open-circuit antenna terminal voltage.

Jarva, in ref. (75), describes some of the problems of radio interference measurements. He breaks the problems down into three areas--the radio interference field, antenna systems, and the correlation of meters. In order to get similar results of radiated interference in different locations, the radio interference field must be controlled. This is generally accomplished by the use of shielded rooms. Typical set-ups are illustrated in Fig. XIII - 6.

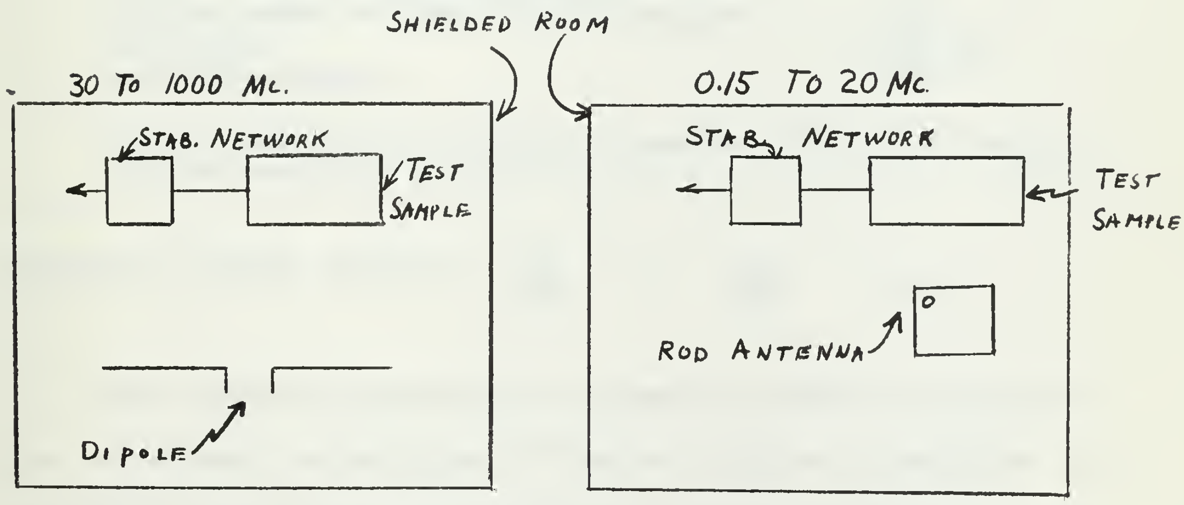

Fig. XIII - 6 Typical Equipment Layouts for Measurements In Shielded Rooms

The standard impedance network in the power leads permits accurate and repeatable measurements of conducted interference and also limits the amount of radiated interference from the leads.

The amount of energy transferred from the field to the input terminals of the interference meter is a function of the antenna length, impedance, location, and orientation. In the VHF and UHF ranges, the standard antenna is a resonant dipole. All calculations assume a dipole antenna impedance of 72 ohms. The voltage induced in the antenna is related to the meter input voltage by the following formula:

$$\frac{\text{ANTENNA INDUCED}}{\text{MICROVOLTS } (\mu v/Kc \text{ or } \mu v)} = \frac{\text{INPUT MICROVOLTS}}{(\mu v/Kc \text{ or } \mu v} \times \left(1 + \frac{72}{\text{METER INPUT } Z}\right)$$

A typical calculation would be as follows for the TS-587 FI meter:

Frequency	150 Mc
Actual meter reading (peak)	47
Hi-frequency microvolt calibration	2
Bandwidth	306 KC
Input impedance	95

Equivalent input microvolts across the input terminals of the receiver = 2 x 47 = 94

$$\text{Antenna induced voltage} = \frac{94}{306} \times 1 \quad \frac{72}{95} = 0.54$$

The primary inaccuracies between meters are found in the broadband correlation. When an impulse is applied to a tuned RF circuit the circuit will oscillate until all the energy is dissipated in the resistance of the circuit. The

duration of the oscillation is inversely proportional to bandwidth. Therefore if a signal is fed to a detector which reproduces the envelope of the RF oscillation, the output pulse will have a peak amplitude directly proportional to and a duration inversely proportional to amplifier bandwidth. Expression of the interference in terms of microvolts per unit bandwidth makes the measurement independent of bandwidth variations. By definition, the rms sine wave input in microvolts required to produce a sine wave second detector peak amplitude equal to that produced by an impulse signal is equal to the intensity of the impulse in microvolts per unit bandwidth times the bandwidth of the receiver in the same units.

Since many of the radio interference field intensity measurements are taken under varying field conditions, the accuracy of the measurements will largely depend on the skill and knowledge of the operator. Many of the variables may be eliminated by proper site selection, shielding of test equipment, etc.

It can be seen from the above that there is no standardized method of measurement that would apply to all types of interference. This has been summarized by Chappell in stating that

> Measurement methods and procedures must be somewhat arbitrary, but in a manner that is as consistent as possible with such practical measurement requirements as sensitivity, operational facility, repeatability of measurement, interpretation of

measurements in terms of the effect of interference on vulnerable electronic systems, level of skill required in operating the equipment, cost, and portability.

CHAPTER XIII
BIBLIOGRAPHY AND ABSTRACTS

1. P. Varlashkin, W. T. Cronenwett, Advanced Receiver and Transmitter Interference Measurement Techniques, Electro-Mechanics Co., Austin, Texas, Supplement to Sections 2 and 3 of the Final Report on Interference Measurement Techniques and Specifications, Contract AF 30(602)1884, Proj. 3766, RADC TN 61-161, May 1, 1960, (AD-260 826).

"Some of the basic parameters to be measured in the evaluation of the radio-frequency characteristics of transmitters and receivers are described. An attempt was made to develop techniques which result in absolute rather than relative data. Emphasis was placed on measurements made at the equipment antenna terminals. Methods of measuring radiated power are described and preliminary test results on several proposed techniques are given. The problems inherent to power-type measurements are analyzed and several methods of performing radiated power measurements are described. Experimental data is given to show the feasibility of methods. A liquid flow calorimetric power measurement device for use in determining calibration accuracies of test equipment as well as for making power measurements directly is described."

2. H. J. Peake, An Aid to the Calculation of Electric Field Strength in the Interference Region, Naval Research Lab., Washington, D. C., R-3222, Jan. 1948, (PB-129 185).

3. C. D. Lafond, Air Force Satellites to Measure Interference, MISSILES AND ROCKETS, Vol. 9, pp. 24-25, Oct. 9, 1961.

Describes an Air Force program to launch a series of electromagnetic interference-measuring satellites. The aim of the program is to determine the amplitude and spectrum characteristics of man-made radio interference that will be encountered by electronic systems operating in high altitude aerospace vehicles.

4. M. M. Newman, Aircraft Radio Interference Measurements, ELECTRICAL ENGINEERING, Vol. 72, pp. 36-40, Jan. 1953.

"For radio interference studies covering a wide frequency range, evaluation of the noise levels requires a great number of measurements for each frequency range and type of communication. A high speed oscillograph is valuable in such work as it can show the effect of each suppressive device on the undesirable transient."

5. T. S. Bailey, Auto Radio Makes Good Test Receiver for Noise Location Work -- Abstract, ELECTRICAL WORLD, Vol. 115, pg. 1328, April 19, 1941.

6. F. J. Morru, B. Fain, M. Deinken, P. Varlashkin, Bridged-T Technique for the Measurement of Spurious Radiation, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"A measuring technique has been developed for determining the magnitude and frequencies of spurious radiations produced by r-f transmitters. The design approach is based upon matching the transmitter into its normal load at the carrier frequency, while a high impedance circuit prevents the carrier from reaching the calibrated receiver. For frequencies removed from the carrier, the calibrated receiver can measure spurious radiation at the transmitter with little or no attenuation. The rejection circuit is a Bridged-T network for which theoretical and experimental data are presented."

7. M. Newman, J. Stahman, Counter Techniques in Interference Measurements, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"Counting Techniques have been developed as a method for measurement of impulsive radio interference based on indicating rates of occurrence of the significant noise-producing properties of interference. An instrument has been constructed to indicate the following quantities, which appear to be the most important noise-producing characteristics of impulsive interference: 1. The average number of times per second that the applied interference waveform exceeds a given rate of rise. 2. The average number of times per second that the applied interference waveform exceeds a given amplitude. 3. The average value of the interference voltage. 4. The rate of occurrence of interference pulses that coincidentally exceed the given rate of rise and amplitude in item 1 and 2 during a period when the average voltage is above a given value."

8. G. Whiting, E. R. Byerley, Correlation Studies of Interference Measurement Techniques, Vol. I, Vol. II, Stoddart Aircraft Radio Co., Inc., 1960.

Discusses various tests of the AN/URM-47, AN/URM-17A, and the NF-105. Includes recommendations for changes

and additions to MIL-I-16910A and antenna comparison studies.

9. W. E. Bower, Determination of Interference Levels, Naval Research Lab., Washington, D. C., R-1537, June 1939, (PB-120 438).

10. F. Greene, M. Solow, Development of VHF Field-Intensity Standards, National Bureau of Standards, Nov. 1949, (TIP G U15658).

"The standards or methods used to establish accurately known values of VHF field-intensity are: (a) the standard-antenna method, and (b) the standard-field method. It is the purpose of this paper to describe two such experimental standards in some detail, the techniques involved for measuring the antenna voltage or current, as well as the propagation tests made to compare the field-intensity values obtained by both methods. The accuracy and limitations of the two methods are also discussed."

11. Electromagnetic Noise Measurement Program Conducted at the Sperry Gyroscope Co. Navigation Inland Facility, (Confid.), Navy Underwater Sound Lab., New London, Conn., July 1960, (AD-318 022).

12. W. Underwood, D. O'Bryhim, Electronics Interference Survey, International Electrical Engineering, Inc., March 1954, (AD-108 761).

13. Establishes Method of Measuring Radio Interference, ELECTRICAL WORLD, Vol. 111, pp. 690-692, 859-862, March 11-25, 1939.

"Describes a method of measuring radio interference utilizing a standard signal generator to produce a standard wave form and a sensitive radio-frequency voltmeter as a measuring instrument. The unknown voltage is compared with the known voltage. Also reviews the factors that influence permissible noise levels, i.e., signal to noise ratio field strength."

14. B. T. Newman, Evaluating Radio Receiver Susceptibility to Interference, ELECTRONICS, Vol. 34, pp. 70-74, April 14, 1961.

"The ever-increasing dependence upon radio communication and the ever-mounting crowding of the radio spectrum have accelerated the demand for high-performance receivers that can operate with maximum

resistance to interference. Thus, there is a need for testing specifications, methods and standards by which a receiver can be graded. This paper describes methods for testing voice communication receivers -- AM, FM and single side band -- and for objectively grading receiver performance in interference."

15. D. Clarke, E. Melvin, Evaluation of Radar and Communication Interference Existing at Air Force Bases, (Confid.), Frederick Research Corp., 1957, (AD-306 129).

16. W. Jona, Evaluation of RFI Pickup Devices and Explanation of the Methods and Limits of Specification No. MIL-I-6181B, Aeronautical Electronic and Electrical Lab., Naval Air Development Center, Johnsville, Pa., Aug. 1955, (AD-75 325).

    Evaluates the relative performance characteristics of the various pickup devices used for the measurement of radio interference, to provide a basis for more uniform, reliable, and generally useful specifications. The radio interference field, antenna systems for radio interference measurements and correlation of meters are discussed.

17. H. Mertel, J. Fischer, Existing Current Probes and Development of New Probes to 1 KMc, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 025).

    "This paper presents the development and the evaluation of current probes to measure conducted interference in the frequency range of 30 cps to 1000 Mc. Four commercially available current probes for the 30 cps to 1000 Mc frequency range were evaluated. Two current probes were developed for the 20 Mc to 1000 Mc frequency region. One current probe was developed to measure interference currents in large diameter cables. The sensitivity of these current probes is sufficient to detect interference currents below most existing specification limits. Several methods are given to calibrate the current probes. In the 300 Mc to 1000 Mc frequency range, the current probes were calibrated by an antenna method."

18. H. E. Dinger, H. G. Paine, Factors Affecting the Accuracy of Radio Noise Meters, Naval Research Laboratory, Feb. 1946, (PB-22 786), INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 35, pg. 81, Jan. 1947.

    "The factors which influence the accuracy of radio-

noise measurements can be divided into two classes: (1) those affecting the accuracy of steady-state sine wave radio frequency measurements and (2) those peculiar to the non-sinusoidal wave shapes of radio noise. Some of the factors can be controlled by suitable standardization of design specifications and methods of measurement, while other factors are dependent on the characteristics of the wave form and on the point at which it is to be measured. Probably the greatest measurement discrepancies can be attributed to differences in the wave collectors employed and to the variations in the charge time "constant" of the metering circuit with differences in noise levels."

19. J. Rutsey, Field Measurement Techniques for Extremely Low Levels of Electromagnetic Interference on High Voltage Transmission Lines, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, (AD-253 015).

"This paper reports on a study of low-level measurements of electromagnetic interference on high voltage transmission lines. The paper deals principally with the development and use of instrument techniques employed in the field and the significant facts determined. Field measurements of electromagnetic interference were obtained by low-level techniques in the frequency range of 20 Mc to 1000 Mc."

20. Selby, Field Strength Measurements, JOURNAL OF RESEARCH OF THE NATIONAL BUREAU OF STANDARDS, SECTION D, Vol. 64, pp. 603-604, Nov. 1960.

"Reviews the progress made in field strength measurement during the period 1957-60. Twenty references are included on which the report was based."

21. Field Strength Measurements and Measuring Devices, Technisch Documentatie Centrom Voor de Krijsmacht (Netherlands), June 1958, (AD-201 419).

22. H. Hasbich, K. Hagenhaus, K. Kegel, The Fight Against Radio Interference, ELEKTROTECHNISCHE ZEITSCHRIFT, Vol. 63, No. 15/16, pp. 177-181, 182-187, 187-191, 23 April 1942.

"In these three papers, the interference problem created by electrical apparatus is treated. Measurement and suppression techniques are given. (1) A discussion of the methods by which permissible residual interference levels are determined by sta-

tistics is presented. Interference suppression by the use of higher desired signal field strength and common-wave broadcasting is discussed. (2) Earlier measuring methods, with references, are included. (3) Interference-suppressing techniques as applied to HF chokes, condensers, series, shunt, and compound-wound motors are described."

23. I. Joffe, Harmonic and Spurious Energy Measurements in High Power Transmitters, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"This paper presents a method for measuring both harmonic and spurious energies at the output terminals of a transmitter. The measuring technique used permits direct measurements to be made on transmitters which have a power output above two watts at frequencies as high as 1500 megacycles. This measuring technique involves sampling the incident energy content at the transmitter output by the use of a directional coupler. The coupler not only attenuates the fundamental energy to levels where standard measuring instruments and attenuator pads can be used, but also minimizes the error due to standing waves that may be caused by a mismatch that exists between the transmitter and the load at harmonic and spurious frequencies."

24. F. L. Greene, S. C. Bartlett, How to Locate and Stop TV Interference, ELECTRICAL WORLD, Vol. 136, No. 21, pp. 99-104, Nov. 19, 1951.

Describes methods and equipment used to locate radio frequency interference. The characteristics of typical interference sources as seen and heard on a television system are discussed.

25. H. A. Myers, Industrial Equipment Spectrum Signatures, Rand Corp., Santa Monica, Calif., Research Memo No. RM-2764, Contract AF 49(638)700, 16 June 1961, (AD-260 921).

"A survey is presented of the radiation characteristics (spectrum signatures) of electrical and electronic equipments such as rectifiers, welders, power lines, switching devices, ignition systems, induction heaters, and electric motors. Several equipment signatures were compiled from interference reports, which indicated that some industrial activities radiate strongly enough to cause interference at ranges up to a few miles, and that most of the

energy is concentrated in the low-frequency portion of the spectrum. The equipments mentioned were measured at very low frequencies, and the graphs show strong and unique signatures in the SLF and ULF (30 to 3000 c) bands."

26. H. T. Head, Influence of Trees on Television Field Strength at UHF, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 48, pp. 1016-1020, June 1960.

27. J. Allen, Insertion Loss Measurements of R-F Suppression Filters with Rated Current Applied, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, Feb. 1957, (AD-234 211).

"The present standardized method for testing the insertion loss of suppression filters as specified in MIL-51D-220 does not take into account insertion loss characteristics under rated load current conditions. The no-load effectiveness of r-f suppression filters employing ferromagnetic core chokes may be considerably reduced when operated at rated load current. Jigs, fixtures, and test equipment have been designed for performing insertion loss measurements of r-f suppression filters with nominal rated current applied. The electrical and mechanical design of this equipment insures accuracy of measurement and maximum facility of operation for the great variety of filter shapes and terminal designs met in practice. Tests were conducted on a random selection of 20 commercial filter samples popularly used in military suppression applications. These test data demonstrate the necessity for revising present procedures for measuring insertion loss."

28. J. Lorch, Instrumentation and Test Procedures, SAE Paper No. 315 B for Meeting March 13-17, 1961.

29. J. I. Chappell, Instrumentation for Interference and Field Strength Measurement, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"Problems of radio interference and field strength measurement are discussed and measurement equipment developed to cope with these problems is described. The problems discussed relate primarily to imposed conditions under which interference and field strength measurements must be made, and the nature of interference together with the particular interference characteristics which are to be measured.

The measurement equipment is described from the standpoint of the measurement system employed and the instrument characteristics that are considered unique."

30. C. V. Aggers, D. F. Foster, C. S. Young, Instruments and Methods of Measuring Radio Noise, ELECTRICAL ENGINEERING TRANSACTIONS, Vol. 59, pp. 178-187, Discussion Transactions, pp. 187-192, March 1943.

"This paper embodies the relevant agreed recommendations of the Joint Coordination Committee on Radio Reception of EEI, NEMA, and RMA, as to the nature, essential characteristics, and performance of an instrument for the measurement of radio-noise voltages. It further gives detailed descriptions of the recommended practices for measuring radio noise directly from low and high-voltage apparatus, for making noise measurements along overhead lines, for determining broadcast field-strength levels, and for methods of collecting data for the establishment of radio-noise standards."

31. A. W. Walters, Interference Analysis of 100 Primary Communication Channels, 224-400 Mc (TDZ - RDZ Equip.), Naval Research Lab., Washington, D. C., R-2967, R-3050, R-3051, R-3052, Dec. 1946.

32. J. J. Arenca, D. C. Ports, Interference Analysis Study, Jansky and Bailey Div., Atlantic Research Corp., Jan. 1962, (AD-283 371).

33. G. L. Hamburger, Interference Measurement -- Effect of Receiver Bandwidth, WIRELESS ENGINEER, Vol. 25, No. 293, pp. 44-54, Feb. 1948; No. 294, pp. 89-97, March 1948.

"This paper deals with the experimental verification of certain concepts about the measurement of radio interference. An examination of the effects of bandwidth on various types of interference, such as fluctuation noise, single and repeated impulses and noise generated by d.c. motors, is carried out. The findings of the investigation have a bearing on the prediction and assessment of electrical interference at different bandwidths and make it sufficient to measure the interference at one standard bandwidth only."

34. C. L. Neal, Interference Measurement Techniques, General Dynamic/Astronautics, San Diego, Calif., April 1962, (AD-277 066).

"The purpose of this program was to develop improved techniques for measuring electromagnetic interference (EMI). Methods were investigated toward reducing measurement cost and time. An investigation was made into the application of a method for measuring the impedance of a closed series loop to measuring conducted interference. The problem of measuring and evaluating transient interference was examined. A definite need for a standard test procedure for solenoid-type equipment was established. A suggested standard procedure is presented. An evaluation was made of the various equipments which are used for the measurement of transient interference. Of particular interest was the applicability of computer techniques. Finally a method was developed by which transients can be directly measured to MIL-I-26600 limit with an oscilloscope."

35. Interference Specification Analysis and Measurements, Final Report, Electro-Mechanics Co., Jan. 1959, (AD-213 296).

"The radio frequency interference testing and specification philosophy are critically reviewed in the light of new requirements. The problems associated with the interpretation of induction field and radiation field intensity measurements are described, and methods of avoiding some of the problems are recommended. Evaluation of the interference potential, of high power linear amplifiers, SSB equipment, and interference field measurement techniques are given."

36. Interference Survey and Suppression Report, Langley Air Force Base, Hampton, Virginia, (Confid.), Frederick Research Corp., Oct. 1957, (AD-157 903).

37. Interference Survey and Suppression Report, Shaw Air Force Base, Sumter, South Carolina, (Confid.), Frederick Research Corp., Bethesda, Md., 1958, (AD-300 062).

38. A. Kall, J. Kugler, Interference Survey of a Large Missile Manufacturing Plant, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, (AD-253 015).

"An intensive Radio Interference Survey was performed in the missile design and manufacturing plant of the Martin Company in Orlando, Florida, to delineate sources of high level interference and to determine the presence of these signals external to the plant. The survey concerned itself with comprehensive

measurements in the frequency range 14 Kc to 10,000 Mc of the interference generated, controlled susceptibility tests on some of the sensitive areas, a one-mile field survey around the plant and the identification of all signals in the plant area. The paper describes the practical problems of conducting these tests, including coordination of equipments under test with the test team, on-the-spot data reduction and analysis, and certain physical problems encountered in the field survey."

39. W. Stoker, K. Martenson, J. Quine, An Investigation of Electromagnetic Coupling Devices for the Measurement of Noise Fields, Rensselaer Polytechnic Institute, Aug. 1952, (AD-7288).

"The project was broken down into three primary phases or techniques. The first phase, the shielded room technique, was initiated to provide a field free volume of space in which to make desired noise field measurements with greater sensitivity. In the second phase, the probe technique, two types of pickup devices were designed to supersede the nine foot whip antenna previously used directly with the URM-3 (noise meter). The third phase, the correlation technique, which was devised to supplement the probe technique is essentially a system to improve the measuring sensitivity by selecting out the desired information in preference to interfering signals."

40. F. Haber, F. Roberts, K. Ya'Coub, Investigation of the Measurement of Radio Interference, Moore School of Electrical Engineering, Univ. of Penna., Oct. 1958, (AD-212 685).

41. F. Haber, J. Diamessis, K. Ya'Coub, Investigations of the Measurement of Radio Interference, Moore School of Electrical Engineering, Univ. of Penna., Nov. 1959, (AD-229 054).

42. F. Haber, J. Diamessis, Investigation of the Measurement of RFI, Report #57, Moore School of Electrical Engineering, Univ. of Penna., Nov. 1960, (AD-245 894).

43. K. Mortenson, An Investigation of Problems Associated with Broadband Interference Measurements, Rensselaer Polytechnic Institute, Feb. 1953, (AD-8738, AD-17 886, AD-21 334, AD-37 283, AD-37 284, AD-40 498, AD-64 493, AD-64 494, AD-64 495, AD-71 910, AD-85 894, AD-91 200).

"The ultimate aim of this study was the development

of sensitive and accurate noise field measuring techniques and the associated measuring equipment which would be used in conjunction with presently existing equipment. The first approach, the cavity technique, was initiated to provide a field free volume of space in which could be made desired voice field measurements with greater sensitivity. Through an elaborate study of fields produced in cavities or screen rooms by different radiators, a complete system of measurement was devised. In the second approach, the probe technique, which provides for the direct measurement of electric fields in "free space", a complete investigation of antenna systems for FI measurement purposes was made. The third approach, the correlation technique, consisted of devising a system to improve measuring sensitivity by selecting the desired information in preference to interfering signals from combined antenna induced voltage."

44. E. Matthews, C. Truax, and others, An Investigation of Problems Associated with Broadband Interference Measurements, Rensselaer Polytechnic Institute, Feb. 1956, (AD-91 200, AD-147 450, AD-206 868, AD-208 241, AD-213 571).

"The only type of radio interference measurements under active investigation at the present time are direct field measuring techniques. This investigation is proceeding in three directions: (1) development of a single-ended antenna coupling system for interim use with a whip antenna up to 30 Mc/s; (2) development of a balanced antenna coupling system for use with a V-biconical antenna over the complete range 0.15 to 1000 Mc/s; and (3) investigation of the use of high-dielectric-constant materials for a low-frequency antenna which will combine small physical height."

45. M. R. Fisher, S. N. Friedman, Investigation of Radio Interference Analysis in a Type B-17 Aircraft, Curtis-Wright Corp., Aug. 1949, (ATI-66652 (3-1)).

"An investigation of radio interference analysis in a Type B-17 bomber is discussed in relation to a performed literature review and the proposed shielded room measurements. The analysis, when completed, is designed to determine the coupling paths between various sources of radio interference in an airplane and affected receivers, and then to find methods of rendering these sources ineffective. Interference

sources considered are the man-made sources inside the aircraft, i.e., rotating machinery and other electrical equipment. The results of the literature survey are presented in the form of a brief discussion of methods currently used on this problem; an outline for the experimental program to be followed in the shielded room measurements is supplied."

46. Investigation of Radio Interference Analysis in a Type B-17 Aircraft, Curtis-Wright Corp., June 1950, (TIP G U15375).

"Radio noise generated in vibrating simulated aircraft structures is discussed."

47. C. Fowler, Investigations of the Measurement of Noise, Moore School of Electrical Engineering, Univ. of Penna., April 1951, (TIP V U19412, TIP V U19573, AD-29 727, AD-29 728, AD-29 729, AD-36 882, AD-51 773, AD-54 516, AD-54 517, AD-75 398, AD-78 125).

"The objectives of this work are to conduct radio interference phenomenon studies, evaluations, investigations, and studies of measurement standards, techniques and effectiveness. The program to fulfill these objectives has two parts. The first part is the evaluation of radio interference measuring sets and related items. In conjunction with this, theoretical and experimental studies are made of the components and circuits in current use, or which might be developed for future use in radio interference measurement. The second part is the measurement of parameters of radio interference sources, together with an attack on a basic problem in this field--the relation between measured parameters and interference effect that is produced by these sources in communications systems."

48. J. H. Evans, Measurement and Suppression of Radio Interference, INSTITUTE OF RADIO ENGINEERS JOURNAL (British), Vol. 9, pp. 46-59, Feb. 1949.

"The paper firstly outlines the nature of Radio Interference and the principles of measurement, goes on to describe measurement techniques as used by a manufacturer, and briefly reviews available methods of suppression and the difficulties encountered in their application. Finally the paper considers recommended suppression limits and points out some anomalies caused by their specification."

49. L. H. Daniel, G. Nole, The Measurement of Interference at Ultra High Frequencies, INSTITUTION OF ELECTRICAL ENGINEERS JOURNAL, Vol. 88, pt. 3, No. 1, pp. 41-49, March 1941.

"The principles of interference measurement are examined in relation to the operation at UHF of frequency-changing circuits. A distinction is shown to exist between the application of the signal and the local oscillation to the same electrode and their application to separate electrodes of the frequency charging value. The design and performance of an apparatus is described which embodies the principle deduced."

50. G. Mole, The Measurement of Interference in the Frequency Range 100-400 Mc/s, British Electrical and Allied Industries Research Association, Rpt. M/T 78, 1944.

51. M. Epstein, H. Sachs, L. Silverman, Measurement of Low-Frequency Electromagnetic Interference, Proceedings of the 6th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1960, (AD-253 015).

"Low-frequency electromagnetic interference is measured utilizing the Hall-effect in intermetallic semi-conductors. Unlike the loop antenna, the Hall-effect sensor is independent of frequency and thus renders a true waveform of the magnetic flux density at any point. The device is compact, thus facilitating the measurement of electromagnetic interference in otherwise inaccessible locations. The principle of operation of the Hall-effect magnetic field probe is given. Described are details of design and construction of a Hall-effect sensor, and results of actual measurements performed are given. Discussed are special shapes of flux collectors which are used in conjunction with the Hall-effect sensor."

52. F. E. Bird, Measurement of Noise, Crosstalk, Volume and Related Quantities in Communication Systems, Coles Signal Lab., Signal Corp Engineering Lab., 1949.

53. Measurement of Radio Interference in Frequency Range 0.15 to 30 Mc--Noise Isolating Unit, British Electrical and Allied Industries Research Association, Rpt. M/T 117, 1953.

54. C. J. Franks, The Measurement of Radio Noise Interference, Radio Manufacturer's Association "Engineer", Nov. 1938.

55. F. Kugler, E. Warchaizer, Measurement of Spurious Emission

From an AM/FM Tuner in Accordance with Part 15 of the FCC Rules and Regulations, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1959, (AD-235 099).

"The paper defines the specific tests required on AM operation and FM operation, and describes some of the difficulties involved in open-field measurements over the FM range in the presence of high ambient levels produced by atmospheric noise and heavily congested signal areas in the spectrum of interest. Some details are presented of suppression techniques to reduce local oscillator radiation consistent with adequate design sensitivity on FM operation."

56. The Measurement of Terminal Interference Voltages Over the Range 150-600 Mc, Post Office Engineering Dept. (British), Sept. 1960, (AD-243 391 L).

57. L. Thomas, Measurement Techniques for Radio Interference, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON INSTRUMENTATION, Vol. 1, pt. 4, pp. 13-15, Oct. 1955.

"Discusses radio interference measurements, requirements and techniques."

58. K. Mortenson, C. Truax, A Method of Making Screen Room Interference Measurements, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, pp. 114-153, Dec. 1954, (AD-76 686).

"A method of making screen room interference measurements is described which employs no operator or measuring equipment within the room. The room is treated as a cavity (below resonance) which is excited by the interference radiating equipment. The cavity field so produced is detected and measured by appropriate wall probes. The measurements obtained are then related to the corresponding "free-space" field intensities such that the "free-space" radiated fields from interfering equipment can be determined without actually making field intensity measurements."

59. N. Lund, Methods of Measuring Adjacent-Band Radiation from Radio Transmitters, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 39, pp. 653-656, June 1951.

"A review of three possible methods of measuring or estimating adjacent-band radiation characteristics of a radio transmitter is given. These three

methods differ in the type of signal applied to the transmitter and may be termed the two-tone, normal signal, and thermal noise methods. Measurements on a multi-channel single-sideband transmitter using each of these methods are presented to show that there is a good correlation between the normal signal and thermal noise methods. An empirical method for calculating the slope of the adjacent-band radiation as a function of frequency from the measured two-tone distortion values is given, and the measured and calculated slopes are shown to be in fairly good agreement."

60. Methods of Measuring Radio Noise, Joint Edison Electric Institute, National Electrical Manufacturers Association and Radio Manufacturers Association Report, NEMA Publication #107, National Electrical Manufacturers Association, New York, N. Y., 10 pp., 1940.

61. H. E. Newell, Jr., A Method for Calculating Electric Field Strength in the Interference Region, Naval Research Lab., Washington, D. C., R-2638, Sept. 1945, (PB-22 674).

62. V. Marcino, A Method of Measuring High Power Transmitter Cabinet and External Wiring Radiation, Proceedings of the 5th Conference on Radio Interference Reduction, Armour Research Foundation, Oct. 1959, (AD- 235 099).

"This paper describes a method for measuring radiated interference from large transmitters without the necessity of placing the transmitter either in an open field or a shielded room. This method utilizes a substitution technique. Therefore, it can be used in any location where measurements can be made conveniently regardless of the local topography because the path loss is automatically compensated for. The choice of a suitable site for the location of the transmitter is limited principally by the availability of sufficiently remote points which lie in the distant or radiation field. This method was developed primarily for TV transmitters, but is applicable for use with any high power transmitter. Test data is provided along with the sample calculation for the harmonic radiations of a 2 kw transmitter. Three series of measurements were made over a three month period in order to verify correlation. In addition, the variation of path loss with frequency over a fixed distance was determined each time for each frequency."

63. L. Espenschied, Methods for Measuring Interfering Noises, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 19, pg. 1951, 1931.

This paper outlines some of the early methods utilized by the Bell System in measuring interfering noises. Some of the methods included are the "warbler method", integration method, noise standard or buzzer method and the circuit noise meter.

64. Methods of Measurement of Radio Interference, British Electrical and Allied Industries Research Association, Rpt. M/T 45, 1936.

65. R. Saul, J. Shami, Microwave Interference and Susceptibility Measurements, INSTRUMENTATION, 1 July 1958.

"The measurement of interference in the range 1000 to 10,000 Mc with a field intensity meter are discussed and illustrated by block diagrams. Measurement procedures are given for radiated, conducted and susceptibility to radiated and conducted interference."

66. Interference Survey Report, Mitchel Air Force Base, Hempstead, N. Y., Frederick Research Corp., Bethesda, Md., Contract AF 30(635)4155, (Confid.), 15 Nov. 1956, (AD-125 647).

67. K. Oishi, New Line Impedance Stabilization Networks for Conducted Radio Interference Measurements up to 100 Megacycles, INSTITUTE OF RADIO ENGINEERS TRANSACTIONS ON RADIO FREQUENCY INTERFERENCE, Vol. RFI-1, No. 2, pp. 2-6, May 1960.

"Two line impedance stabilization networks-- a single unit and a dual unit--for the measurement of conducted radio interference have been redesigned from the present line impedance stabilization network to yield a smooth repeatable response up to 100 Mc."

68. H. Dinger, W. Garner, A New Method of Calibrating Field Strength Measuring Equipment, Naval Research Lab., Washington, D. C., Nov. 1952, (AD-1033).

69. H. Kilberg, New System Design for Detecting Interference to Missiles, ELECTRONIC INDUSTRIES, Vol. 19, pp. 170-173, April 1960.

"By 1959 a new spectrum surveillance system designed

on functional concepts through exploratory engineering was needed. In June, a rudimentary system with automatic search capabilities was implemented for the frequency range from 40 to 1000 Mc (at Cape Canaveral). The system provided frequency measurement, signal strength measurement, direction finding and a detection threshold of -120 dbm."

70. F. Conrad, On the Measurement of High-Frequency Interference, ELEKTRISCHE NACHRICHTENTECHNIK, Vol. 18, No. 6, pp. 126-133, June 1941.

"States that the frequency spectrum of HF interference must be determined before adequate measurement can be designed. These spectra must be known both at the source and after radiation or conduction from the source. That ultra short wave emissions in the decimetric wave range from improperly shielded apparatus will interfere with interference measurements. Discusses the characteristics which measuring devices must have in order to properly measure HF interference levels. The device can be identical to a standard receiver for all stages up to rectifier. However the rectifier must not be overcontrolled. The use of superheterodyne receivers for noise intensity measurements is discussed. In most cases, consistent results from different equipments are almost impossible to obtain unless the equipments are electrically and electro-acoustically identical."

71. C. G. Seright, Open-Field Test Facilities for Measurement of Incidental Receiver Radiation, RCA REVIEW, Vol. 12, pp. 45-52, March 1951, (ATI 107 806 (3-4)).

"The problem of evaluation and reduction of interference radiation propensities of television and FM receivers, and of the lack of standards and facilities to permit measurement in terms of actual inductive or radiated field intensity is discussed. Open field facilities for such measurements, recently set up on the grounds of RCA Laboratories at Princeton, N. J., have been placed in operation. Preliminary results appear to be up to expectations."

72. W. J. Cook, Pinpointing Radio Interference by Airplane Cuts Time 80%, ELECTRICAL WORLD, Vol. 146, pg. 114, Dec. 24, 1956.

"Pinpointing radio interference sources from a small airplane flying over a hard-to-patrol line has proved effective for Georgia Power and Light Co."

73. M. Abromavage, Preliminary Survey of Electromagnetic Environment at the U. S. Naval Weapon Laboratory, Dahlgren, Virginia, Jansky and Bailey, Inc., Dec. 1960, (AD-246 747).

74. J. Goldberg, Problems in the Measurement of Radio Noise Interference, Stanford Research Inst., May 1952, (AD-10 862).

"The difficult problem of measuring power level and the time and frequency characteristics of an interference is encountered in all work on radio interference. Some of the standard difficulties which occur in calibrating measuring equipment and interpreting the results are discussed in this report. Elementary concepts of communications noise measurement are introduced, with information on the characteristics and origins of common radio noise and interference. Responses to noise and interference of key components of noise measurement instruments are described. Supplementary descriptions of artificial noise sources and standard noise ratings of receiving antenna are given. The problem of errors in measurement is discussed with respect to errors of interpretation, errors in the use of equipment and defects in the equipment. Recommendations are made as to desirable calibration procedures."

75. W. E. Pakala, Problems of Measuring Radio Interference, WESTINGHOUSE ENGINEER, Vol. 18, pp. 71-74, May 1958.

Describes in general terms the terminology used in RFI measurement and outlines methods for measurement on high and low voltage electrical apparatus. Military requirements and specifications as well as radiation measurements required by the FCC are also reviewed briefly.

76. W. Jarva, Problems of Radio Interference Measurements, Aeronautical Electrical and Electronics Lab., Naval Air Development Center, Johnsville, Pa., Rpt. NADC-EL-N54149, (AD-60 699).

"Difficulties generally met in the radio interference specification testing of electronic or electrical equipment to be installed in military aircraft are discussed in this report. The problem is broken down into three parts dealing with the radio interference field, antenna systems, and the correlation of meters. A few specific cases where unusual results were obtained are also discussed and calculations are given relating standard limits and input

microvolt limits for a number of meters."

77. W. Jarva, Problems of Radio Interference Measurements, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"Difficulties which are generally met with in the radio interference specification testing of electronic or electrical equipment to be installed in military aircraft are discussed. The problem is broken down into three parts dealing with the radio interference field, antenna systems and the correlation of meters. A few specific cases where unusual results were obtained are also discussed and calculations are given relating standard limits and input microvolt limits for a number of meters."

78. Procedure for Conducting Radio Interference Field Tests of the Suppression Systems Applied to Ordnance Vehicles, (Manual IM-1), Detroit Signal Lab., June 1945, (PB L 85939).

"The purpose of this manual is to present a standardized procedure for conducting radio-interference field tests of the suppression systems applied to ordnance vehicles. The manual is divided into four parts: I. Interpretation of results; II. Assembly of equipment; III. Description of control box assembly; and IV. Test procedure using modified radio receivers BC-312, 603, and 683."

79. P. Wilson, Jr., Quicker and Simpler Means for Interference Detection and Suppression, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, Feb. 1957, (AD-234 211).

"By the use of broadband-conducted measuring techniques, it is possible to provide instrumentation which may be used by less skilled personnel to do trouble-shooting, monitor quality control and provide an inexpensive means for checking all production rather than sampling. This method also provides a means for detection of malfunctioning of electrical and electronic equipment; the detection of the presence of interference on power lines and is an aid in the design of less expensive test equipment."

80. A. Thompson, RFI at the Harvard Radio Astronomy Station, Harvard College, 1957, (AD-146 852).

"This report gives details of a survey of the radio interference at the Harvard Radio Astronomy Station at Cook Flat near Fort Davis, Texas. The information is derived from three sources. First, a survey was made with a Noise and Field Intensity Meter type NF-105, covering the range from 20 to 200 Mc/s. Second, observations were made in the range 20 to 40 Mc/s with a standard communications receiver. Finally the records taken with the solar spectrum analysis equipment, which covers 100 to 580 Mc/s, were scanned for any further interference."

81. H. E. Dinger, RFI Measurements and Standards, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 50, No. 5, pp. 1312-1316, May 1962.

"Radio noise parameters outlined; standardization of RF interference measurements from early efforts and postwar efforts."

82. R. Wolfe, E. Erickson and others, Radio Frequency Anechoic Laboratory Design Study, HRB-Singer, Inc., State College, Pa., Rpt. No. 289.1-F, Contract AF 30 (602)2445, Nov. 1961, (AD-273 225).

"Requirements of an RF anechoic chamber designed to perform as a general radiation measurements laboratory were studied. Primarily, the chamber would be used to perform radio frequency interference measurements on military equipment. The intended uses criteria are established to obtain the requirements for minimal performance and for optimum performance resulting in specific design values for a chamber to meet either of these two sets of requirements. The investigation extends to present a theoretical review of RF absorber and shielding material characteristics and their application to chamber design, and a derivation of geometrical shapes for both two dimensional and three dimensional radiation pattern measurements. Finally measurement techniques are considered with regard to the improvement of chamber performance characteristics by instrumentation discrimination."

83. Radio Interference Suppression Techniques--A Guide for Manufacturers, Coles Signal Lab., Nov. 1953, (AD-21 192).

84. R. H. Mertz, Radio Interference Tests Detect Defects, ELECTRICAL WORLD NEWS, Vol. 142, pp. 56-57, Oct. 11, 1954.

85. H. J. Tyzzer, Radio Noise Measurement, ELECTRICAL MANUFACTURING, Vol. 63, pp. 93-95, Nov. 1958.

86. C. Bayhardt, Radio Noise Meter and Its Application, GENERAL ELECTRIC REVIEW, Vol. 36, pg. 201, 1933.

Describes an early portable radio noise meter using a 400 cycle 50% modulated sine wave for calibration. It covered the broadcast band.

87. P. A. Guerino, R. B. Owen, R. E. Davis, Receiver and Transmitter (RCM) Interference Tests, Naval Research Lab. Washington, D. C., R-2664, Oct. 1948, (PB-122 775).

88. L. R. Pangburn, Relationship Between Broadband Interference Measurements (DBMC) and Pulsed-CW Signals, INSTITUTE OF RADIO ENGINEERS NATIONAL CONVENTION RECORD, Vol. 9, pt. 8, pp. 14-18, 1961.

89. J. Berliner, J. Augustine, Results of UHF Manual Environment Test Program at RADC, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pg. 222, Feb. 1957, (AD-234 211).

"Description of test set-ups, methods of measurements, results and conclusions. Interference level prediction is presented."

90. F. E. Sanford, W. Weise, Review of Radio Interference Investigations, ELECTRICAL ENGINEERING, Vol. 56, pp. 1248-1256, Oct. 1937.

"The purpose of this paper is to review several factors of particular interest to the electric utilities, who supply service to both the radio and many of the interference sources. A relatively new form of interference effect--external cross modulation is described. In conclusion, a parallel is drawn to the familiar coordination activities on wired communication lines and electric power systems."

91. 746th AC and W (P-86) Site, Oklahoma City, Oklahoma, Suppression Site (Unclassified Title) Interference Survey Report, Frederick Research Corp., Bethesda, Md., 15 Dec. 1955, Rpt. No. FRC 55-P22-5, Contract AF 30(635)4155, (Confid.), (AD-129 230).

92. A Simulator for the Formulation of Interference Specifications and for the Determination of Specification Compliance, Pt. 3, A Study of Some of the Parameters Required for the Simulation of an Electromagnetic Environment, Electro-Mechanic Co., March 1960, (AD-260 826).

93. K. Ikrath, Some Concepts, Theory, and Implementation of

Radio Interference Measurement, Army Signal Engineering Lab., Oct. 1957, (AD-149 450).

94. Some Considerations in Measurement and Suppression of Radio Interference, British Electrical and Allied Industries Research Association, Rpt. M/T 30, 1934.

95. W. Jarva, Some Unusual Aspects of MIL-I-6181B Radio Interference Measurements, Proceedings of the 3rd Conference on Radio Interference Reduction, Armour Research Foundation, pp. 89-97, Feb. 1957, (AD-234 211).

"Laboratory investigations reveal that present methods of measuring radiated interference may result in inaccuracies of as much as 100-1. An exposition of important but subtle defects in specification procedure and measuring equipment is derived from electromagnetic field theory for distances short compared to a wavelength. Consideration is given to often-recurring practical situations which cause maximum inaccuracy. Marked changes in the test setup and test equipment design are suggested which provide substantial improvement in repeatability and accuracy of measurements. The present calibration of meters and their loop antennae results in meaningless measured values in the induction field. A discussion of the fundamental problem is presented and a more logical system of units is presented."

96. F. Greene, A Source of Error in the Measurement of Radiated Harmonics, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 40, No. 4, pp. 486-487, April 1952.

"A source of error, known to be present in VHF field intensity meters employing broadband radio frequency input circuits, has been briefly investigated. The error is caused by harmonic generation in the receiver resulting from insufficient selectivity, and nonlinearity of r-f or mixer stages in the presence of a strong fundamental. The magnitude of the second and third harmonics generated internally were determined as a function of the level of the applied r-f fundamental for a receiver having one particular type of r-f input circuit. Errors in the measurement of the fundamental, caused by intermodulation occurring in the presence of a stronger interfering carrier of different frequency, are also briefly discussed."

97. J. Capen, Spectral Measurements of Radio Interference with A Coherent Memory Filter, Proceedings of the 7th

Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 205).

"A different approach to the spectrum analysis problem has been proposed. This approach utilizes a recirculating delay-line-heterodyne feedback loop to obtain an excellent approximation of the signal spectrum in real time. This device is known as the coherent memory filter, and it has the advantages, with respect to the bank of filters, of being capable of observing rapid changes in the input spectrum that occur from one processing period to the next, and of providing continuous spectral coverage. In addition, the processing period, or integration time, of the coherent memory filter is easily adjustable, so that variable-resolution analysis of nonstationary spectra is possible. This is the equivalent of continually changing the number of filters, and their bandwidths, in a filter bank consisting of hundreds of filters."

98. W. Edson, V. Price, Spurious Frequency Measurements in Transmission Lines--A Comparative Review of Available Techniques, Proceedings of the 7th Conference on Radio Interference Reduction, Armour Research Foundation, Nov. 1961, (AD-276 025).

"Several methods for measurement of spurious signal levels in microwave transmission lines have been developed in recent years in response to a growing need for control of radio interference. This paper compares these methods from the standpoint of accuracy, speed, information content and applicability to the present spectrum signature collection plan. To supplement this review, some suggestions are given for application of these methods or improvements thereof to spectrum signature collection, production testing of components and systems, and standards laboratories."

99. Standards on Electron Devices: Methods of Measuring Noise, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 41, pt. 3, pg. 890, July 1953.

This paper indicates methods for noise factor measurements. Three general methods of measurement are discussed. (1) CW-Signal Generator Method, (2) Dispersed-Signal Source Method, (3) Comparison Method. IRE standard definitions of some of the terms used in this Standard are listed in the Appendix.

100. Standards on Radio Receivers: Open Field Method of Measurement of Spurious Radiation from FM and TV Broadcast Receivers, INSTITUTE OF RADIO ENGINEERS PROCEEDINGS, Vol. 39, pp. 803-806, July 1951.

"This standard describes the potential sources of spurious radiation from frequency modulation and television broadcast receivers and sets up methods of measurement whereby the strength of some of these radiations may be determined. Where the methods for the two classes of receivers differ, the specifications for each are outlined."

101. Richard R. Hazen, The Study and Investigation of R. F. Noise Generator Capabilities and Noise Measurement Techniques, Interim Scientific Report No. 1, 1 Jan. to 31 Dec. 1961, Contract AF 33(616)7718, Jan. 1962, (AD-272 276).

"Investigations were made into problems related to the performance capabilities of wide band RF noise generators and RF noise measurement techniques. The inherent characteristics of 2 types of noise generators were studied and noise measurement techniques were developed which are suitable for detecting and accurately instrumenting RF noise energy generated by the devices. The devices studied were the JAN6700 microwave beam switching tube and the AF12 wide band noise generator. Several methods were investigated to increase the noise power output of the devices; however, the most promising method proved unpractical because of circuit complexity. Four methods of measuring noise were investigated and 3 were quite successful."

102. H. A. Thomas, Subjective Method of Measuring Radio Noise, INSTITUTION OF ELECTRICAL ENGINEERS PROCEEDINGS, Vol. 97, pt. 3, pp. 329-334, Sept. 1950.

"Various methods of measuring radio noise are described, and an account is given of a subjective method which was developed during the last war to obtain data quickly from a large number of locations. It was necessary to make use of simple equipment capable of being operated by personnel having little experience of radio measurements, and, with this object in view, experiments were conducted which demonstrated the efficacy of the subjective method. The equipment described is capable of measuring to an accuracy of $\pm$ 5 db any noise level greater than 1μV/m over the frequency range 2.5-20 Mc/s. The

arrangements for observing, transmitting, collecting and analyzing the data are briefly described."

103. Technical Progress Concerning the Measurement of Radio-Electric Interference, translated by J. Pfister and J. P. Buclin, R. I. (Suisse), May 1955.

104. A Technique for the Measurement of Spurious Radiation, Electro-Mechanics Co., June 1953, Int. Rpt. #1 (AD-13 870); Int. Rpt. #2 (AD-23 619); Int. Rpt. #3 (AD-26 620); Final Rpt. (AD-36 661).

"A measuring technique has been developed for determining the magnitudes and frequencies of spurious radiations produced by RF transmitters. The design approach is based upon matching the transmitter into the normal load at the carrier frequency, while a high impedance circuit prevents the carrier from reaching the calibrated receiver. For frequencies removed from the carrier, the calibrated receiver can measure spurious radiation at the transmitter with little or no attenuation. The rejection network is a Bridged-T circuit, three separate units are required to cover the frequency range from 15 KC to 1000 Mc. Theoretical and experimental data is given for the Bridged-T network. Detailed operational procedures are given for the use of the measurement technique."

105. W. Jarva, Techniques for the Measurement of Spurious Radiations and Harmonics from Transmitters, Proceedings of the Conference on Radio Interference Reduction, Armour Research Foundation, Dec. 1954, (AD-76 686).

"Methods of measurements are described for spurious signals emitted by transmitters which are intended to operate into a 50-ohm antenna and also for high impedance transmitters which are intended to operate at low frequencies into a non-resonant wire antenna."

106. W. Jarva, Techniques for the Measurement of Spurious Radiations and Harmonics from Transmitters, Naval Air Development Center, Johnsville, Pa., May 1955, (AD-64 593).

"Simplified methods for making the measurements using General Radio Adjustable Attenuator 874-GA and an easily constructed capacitor attenuator. The measurement methods discussed herein pertain only to unbalanced transmitters; balanced transmitters are not used in aircraft. Although the methods described herein involve military specification testing in particular, they may also be used for

measuring spurious signals as much as 100 db below the fundamental and up to frequencies as high as 4000 Mc."

107. Tolerable Limits and Special Methods of Measurement of Radio Interference from Wire Communications and Signal Systems, Canadian Electrical Code-- IV: Radio; Canadian Standards Association, C22:4, n 107, 1949.

108. Tolerable Limits of RI from RF Generators--Industrial, Medical, Scientific, Canadian Standards Association, C22:4, n 106, 1949.

109. J. Brooks, The Two Current-Probe Method of Measuring Conducted RFI, Naval Civil Engineering Lab., Port Hueneme, Calif., Sept. 1962.

"A brief discussion is presented on the limitations and uncertainties of the presently accepted method using Line-Impedance-Stabilization Networks (LISN). These limitations stem from the fact that no information is obtained concerning the impedance values of the circuit being measured during a noise measurement. A method of determining the impedance values of the circuit has been worked out which requires the use of two current-probes. Either the noise-source impedance or the load impedance or both may be determined by this method. Two separate measurements and calculations are required however, one to determine the magnitude of the impedance and the other to determine the phase angle."

110. VHF and UHF Radio Interference Tests at Point Loma, Navy Electronics Lab., San Diego, Calif., Rpt. No. 25, 1948.

111. C. M. Adams, What's That Noise? How to Trace and Cure Local Interference, RADIO NEWS, Vol. 22, pg. 23+, Aug. 1939.

CHAPTER XIV

CONCLUSIONS AND RECOMMENDATIONS

As has been repeatedly pointed out throughout this study the need for minimizing the effects of radio frequency interference is of ever-increasing importance. Not only does RFI take up valuable space in the radio frequency spectrum but it can, for example, cause costly failures in missile guidance systems and microwave data links. With the advent of satellite communication systems as well as space probes and radio telescope exploration of space the necessity of RFI control becomes an international problem. In order to solve this problem it is considered that efforts should be directed towards establishment of:

(1) Universally accepted standards of RFI measurement and uniform permissible levels of interference;

(2) Methods and measurement equipment that will rapidly identify and locate RFI.

STANDARDS

A comparison of European and American measuring equipment and techniques reveals considerable difference. For instance, in the measurement of ignition interference, peak values are measured in the U. S. while the international standard of the International Committee on Radio Interference (C.I.S.P.R.) measures quasi-peak values. Measurement test set-ups relating distance and azimuth angle from the

source to the measuring device differ. Figure III - 2 graphically illustrates the wide variation in permissible field strength levels. For instance in the frequency range above 100 mc the United Kingdom permits twice the level of interference as that considered tolerable by the United States. Other nations have still different limits.

At the present time the Federal Communication Commission limits on interference from incidental radiation devices are very general and the operator of such devices is responsible for eliminating the harmful interference. It is our opinion that the average citizen is not even aware that he may have RFI generators in his possession, to say nothing of knowing how to eliminate the RFI. Other countries, such as Canada and Great Britain, have taken positive steps to ensure that many such RFI generating devices have suppression devices applied to them.

METHODS AND EQUIPMENT

Although numerous measurements of common types of interference have been made in the LF through the UHF portion of the radio-frequency spectrum, very few measurements have been taken in the ELF and VLF bands or frequencies in excess of 1 kmc. Since most sources of man-made interference have unique spectrum signatures, a compilation of these signatures covering the radio spectrum from the ELF through the SHF bands would serve as a valuable aid in quickly identifying a source of interference. It has been shown that this

can be readily accomplished even in relatively high levels of ambient noise.

In order to obtain an interference spectrum signature there is a need for a frequency swept RFI intensity meter. The RFI meter should be able to cover the spectrum from 0 to 30 kmc with a minimum number of RF tuning heads and associated antennas. The meter's "print out" of the spectrum signature should be in terms of frequency versus absolute field intensity.

The establishment of maximum limits of radiation to ordnance has been hampered by the lack of success in development of instrumented electroexplosive devices. Although no reference could be found to such limits it is assumed that standards have been established and that they are very conservative. It is quite possible that over-conservative standards may lead to unnecessary operating and handling procedures. The same conclusions could be reached in regard to standards for maximum power density allowable in refueling areas.

Based on the foregoing conclusions, the following recommendations are made:

(1) International standards for measuring radio frequency interference be adopted, including standardized test equipment and uniform limits of permissible interference.

(2) Consideration be given to the establishment of specific FCC tolerable limits of RFI that may be generated

by motor vehicles and other incidental radiation devices and that manufacturers be made responsible for limiting their products to such limits at the time the products are sold.

(3) Measurements should be taken of common sources of RFI in the ELF and VLF bands and in excess of 1 kmc and recorded as part of the spectrum signature of man-made non-communication type RFI.

(4) Continuing efforts should be made to develop a RFI field intensity meter capable of providing a RFI spectrum signature rapidly and accurately.

(5) Continued efforts should be exerted to design instrumented EED's in order that more realistic standards be established for maximum allowable radiation to ordnance devices.

(6) Efforts should be made to develop an instrument for evaluating explosive hazards due to volatile gases.

APPENDIX A

DEFINITIONS

1. Ambient interference -- The interference level resulting from sources other than that being measured. This includes atmospherics, interference from man-made equipment and internal noise of the interference measuring set.
2. Asymmetrical and symmetrical components -- When two voltages of a given frequency are present on the supply lines and these voltages differ both in amplitude and phase each voltage can be resolved into symmetrical components, i.e., consisting of voltages of equal amplitude and opposite phase between the conductors and ground, and asymmetrical components consisting of equal amplitudes and the same phase between the conductors and ground.
3. Atmospheric interference -- Interference caused by the natural disturbances in the atmosphere. Produced principally by lightning discharges. Basically of the impulsive type and is the principal limitation at lower frequencies. Other sources are static discharges from snow, dust, rain and cosmic noise.
4. Bond -- A low resistance element that joins two or more electrically conductive parts together.
5. Broadband interference -- The interference is not confined to one specific frequency but may be spread over a large range of frequencies.

6. Continuous wave (CW) interference -- Interference having a narrow radio frequency spectrum. Examples are single frequencies radiating from electronic equipment such as oscillator spurious emissions.

7. dbm -- Decibels relative to 1 milliwatt equals $10 \log_{10} P$ where P is the power in milliwatts.

8. EED -- Electroexplosive devices that provide electrical switching, to actuate and perform mechanical functions, and to ignite explosive and propulsive sequences in ordnance systems.

9. EHV -- Extra high voltage transmission lines.

10. Grounding -- A process of electrically connecting parts and/or structures to earth potential.

11. Harmonics -- A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.

12. HERO -- Hazards of Electromagnetic Radiation to Ordnance: a study under the sponsorship of the Bureau of Naval Weapons.

13. Impulse -- Impulse interference is characterized by a systematic or periodic repetition of pulses.

14. Incidental radiation device -- A device that radiates radio frequency energy during the course of its operation although the device is not intentionally designed to generate radio frequency energy.

15. Insertion loss -- Insertion loss is defined as the ratio

of voltages existing across a load impedance before and after "inserting" or connecting the suppression to be tested in the circuit.

16. Interference -- Radio frequency interference shall be defined as any electrical disturbance which causes an undesirable response or malfunction in any electronic circuit.
17. ISM -- Industrial, Scientific and Medical equipment whose radiation is regulated by Parts 15 and 18 of the FCC rules.
18. Microvolts/meter/unit bandwidth -- By definition the rms sine wave input in microvolts required to produce a sine wave second detector peak amplitude equal to that produced by an impulse signal is equal to the intensity of the impulse in microvolts per unit bandwidth times the bandwidth of the receiver in the same units.
19. Narrowband -- Narrowband interference is characterized by the fact that it is limited to a discrete frequency.
20. Peak measurements -- Interference measurements proportional to the peak amplitude of an interfering signal. It is usually the voltage required at the second detector to bring it to the threshold of audibility.
21. Quasi-peak measurements (QP) -- Interference measurements proportional to the "nuisance" value of an interfering signal. Quasi-peaks provide a higher reading on impulsive interference than a field intensity reading. It

can approach the field intensity reading for CW interference.

22. RAD HAZ -- (Radiation Hazards) A program of study under the sponsorship of the Bureau of Ships.

23. Radio coordination -- The cooperative effort between groups representing electric-apparatus manufacturers, power companies, and radio-apparatus manufacturers to control the influence on radio reception of electric power apparatus and circuits.

24. Random interference -- Random interference is described as pulses having no clear or definite repetition rate.

25. RI -- Radio influence level of a power transmission line.

26. RIV -- (Radio Influence Voltage) The measured voltage that causes radio interference to emanate from electric power transmission lines.

27. Spectrum analyzer -- A radio receiver that provides a plot of a specified frequency range on a cathode-ray tube screen, portraying a graph of amplitude versus frequency.

28. Spurious emission -- Emission of electromagnetic energy at any frequency or frequencies other than the designed operating frequency.

29. Suppression of interference -- The reduction of interference effects by proper engineering techniques applied at the source, along the transmission path, or at the affected electronic equipment.

30. TIF -- (Telephone Influence Factor) The telephone influence factor is used as an index to the effect of distortion of the voltage and current-wave shapes on the inductive influence in coordination studies with communication systems.

APPENDIX B

PARTIAL LIST OF MILITARY STANDARDS AND SPECIFICATIONS APPLICABLE TO RADIO FREQUENCY INTERFERENCE CONTROL AND MEASUREMENT

MIL-C-11693B(2)	Capacitors, feed through, Radio Interference Reduction, AC and DC, (Hermetically sealed in metallic cases), General Specification for (with Supplement 1 dated 9 March 1960) Supplement 1 DA
MIL-C-12889A(2)	Capacitors, by-pass, Radio Interference Reduction, paper dielectric, AC and DC, (Hermetically sealed in metallic cases) General Specification for
MIL-E-8881	Enclosure, Electromagnetic-Shielding, Demountable, Prefabricated General Specification for (ASG)
MIL-F-15733D(1)	Filters, Radio Interference
MIL-I-6181D (change 2)	Interference Control Requirements, Aircraft Equipment
MIL-I-11683A	Interference Suppression, Radio, Requirements for Engine Generators and Miscellaneous Engines (Supersedes 7-3004 and 71-3214)
MIL-I-0011683B	Interference Suppression, Radio, Requirements for Engine Generators and Miscellaneous Engines
MIL-I-11748B(3)	Interference Reduction for Electric Equipment
MIL-I-16165D	Interference Shielding, Engine Electrical Systems
MIL-I-16910A(3)	Interference Measurement, Radio, Methods and Limits, 14 Kilocycles to 1000 Megacycles
MIL-I-17623(3)	Interference, Radio, Requirements, Methods and Limits (14 KC to 1000 MC) for Electric Office Machines, Printing and Lithographic Equipment (Navy)
MIL-I-26600(2) (Change 1)	Interference Control Requirements, Aeronautical Equipment

MIL-R-12944A	Resistors, Suppressors, Ignition Interference
MIL-S-5786	Suppressor, Electrical Noise, Radio Frequency (Supersedes 32331)
MIL-S-10379A(1)	Suppression, Radio Interference General Requirement for Vehicles (and Vehicular subassemblies)
MIL-S-12348A	Suppression, Radio Interference General Requirement
MIL-S-12422	Shields, Radio Frequency Interference (General Purpose for Battery Ignition, Internal Combustion Engines)
MIL-S-13237A	Suppression, Radio Interference Requirements for Watercraft
MIL-STD-285	Attenuation Measurements for Enclosures
MIL-STD-449A	Measurement of Radio Frequency Spectrum Characteristics

APPENDIX C

SOURCES USED IN COMPILING BIBLIOGRAPHIES

The following sources were consulted in our library search for articles on radio frequency interference:

Air Technical Intelligence Technical Data Digest, U. S. Army Air Forces, Wright Field, Dayton, Ohio, Vol. 12, No. 1, July 1947 through Vol. 17, No. 11, November 1952.

Applied Science and Technology Index, H. W. Wilson Company, New York, N. Y., Vol. 46, No. 1, January 1958 through Vol. 50, No. 11, December 1962.

Battelle Technical Review, Battelle Memorial Institute, Columbus 1, Ohio, Vol. 1, No. 1, January 1952 through Vol. 11, No. 1, January 1963.

Bibliographic Index, H. W. Wilson Company, New York, N. Y., Vol. 2, 1943/46 through December 1962.

Bibliography of Scientific and Industrial Reports, Office of the Publication Board, U. S. Department of Commerce, Vol. 1, No. 1, January 11, 1945 through Vol. 11, No. 6, June 1949, (with Vol. 12, No. 1, July 1949, title changed to Bibliography of Technical Reports).

Bibliography of Technical Reports, Office of Technical Services, U. S. Department of Commerce, Vol. 12, No. 1, July 1949 through Vol. 22, No. 3, September 17, 1954, (with Vol. 22, No. 4, October 1954, title changed to U. S. Government Research Reports).

Electronics Abstracts, Parks International Publications, Inc., Chicago, Illinois, 1956.

Electronic Engineering Master Index, Electronics Research Publishing Company, New York, N. Y., Vol. 1 (1925 - 1945), Vol. 2 (1946), Vol. 3 (1947 - 1948), Vol. 4 (1949).

Electronics Express, International Physical Index, Inc., New York 35, N. Y., Vol. 1, No. 0, March 1958 through Vol. 5, No. 6, 1963.

Engineering Index, Engineering Index, Inc., New York City, N. Y., 1935 through January 1963.

Industrial Arts Index, H. W. Wilson Company, New York, N. Y., Vol. 20, 1932 through Vol. 45, 1957, (with Vol. 46, No. 1, January 1958, title changed to Applied Science and Technology Index)

Keywords Index to U. S. Government Technical Reports, Office of Technical Services, U. S. Department of Commerce, Vol. 1, No. 1, June 15, 1962 through Vol. 1, No. 16, February 1, 1963.

Lectrodex, Radio Magazines, Inc., Mineola, New York, Vol. 11, No. 1, January - February 1956, through Vol. 17, No. 5, September - October 1962.

Radiofile, Richard H. Dorf, New York 24, N. Y., 1946 annual through 1955 annual, (with Vol. 11, No. 1, January - February 1956, title changed to Lectrodex).

Reader's Guide to Periodical Literature, H. W. Wilson Company, New York, N. Y., Vol. 9, July 1932 through Vol. 62, No. 16, November 10, 1962.

Science Abstracts - Section B: Electrical Engineering, The Institute of Electrical Engineers, London, England, Vol. 38, 1935 through Vol. 66, No. 781, January 1963.

Technical Abstract Bulletins, Armed Services Technical Information Agency, Arlington, Virginia, Bulletin No. U-1, March 13, 1953 through Bulletin No. U62-4-2, October 15, 1962.

Technical Translations, Office of Technical Services, U. S. Department of Commerce, Vol. 1, No. 1, January 2, 1959 through Vol. 8, No. 11, December 15, 1962.

U. S. Government Research Reports, Office of Technical Services, U. S. Department of Commerce, Vol. 22, No. 4, October 1954 through Vol. 38, No. 2, January 20, 1963.

U. S. Naval Bureau of Ships Journal, U. S. Naval Bureau of Ships, Washington, D. C., Vol. 1, No. 1, May 1952 through Vol. 11, No. 8, January 1963.

Sources of U. S. Naval Postgraduate School Technical Library:
- Card catalogs for books
- Files of:
  - ASTIA Document Abstract cards
  - ASTIA Document Microcards
  - Technical Information Pilot cards and microcards
  - Air Technical Index cards
- Vertical files